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The Water-Energy Nexus—An Earth Science Perspective

Circular 1407

U.S. Department of the Interior
U.S. Geological Survey

Cover photographs (clockwise):

- ***A.*** A drill rig in the Fayetteville Shale gas play of Arkansas. Photograph by Bill Cunningham, U.S. Geological Survey (USGS).
- ***B.*** Ivanpah Solar Electric Generating System in the Mojave Desert of California. Photograph by NRG Energy, Inc., used with permission.
- ***C.*** Coalbed methane production water discharge near Tongue River, Montana. Photograph by David A. Nimick, USGS.
- ***D.*** Browns Ferry nuclear power station. Photograph by U.S. Nuclear Regulatory Commission.
- ***E.*** Farm. Photograph by USGS.
- ***F.*** McNenny State Fish Hatchery, South Dakota. Photograph by Michael T. Carter.
- ***G.*** Oil pumper. Photograph by Bureau of Land Management.
- ***H.*** Cooling towers at nuclear power plant. Photograph by USGS.
- ***I.*** Coal-mining operation. Photograph by Bureau of Land Management.
- ***J.*** Dam and reservoir. Photograph by USGS.

Background photograph: Yucca Mountain crest. Photograph by U.S. Department of Energy.

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U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	6.290	barrel (oil, 1 barrel = 42 gal)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
cubic hectare (ha^3)	810.7	acre-foot (acre-ft)
	Flow rate	
cubic meter per year (m^3/yr)	0.000811	acre-foot per year (acre-ft/yr)
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton per day	1.102	ton per day (ton/d)
	Energy	
joule (J)	0.0000002	kilowatthour (kWh)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$°F=(1.8\times°C)+32$

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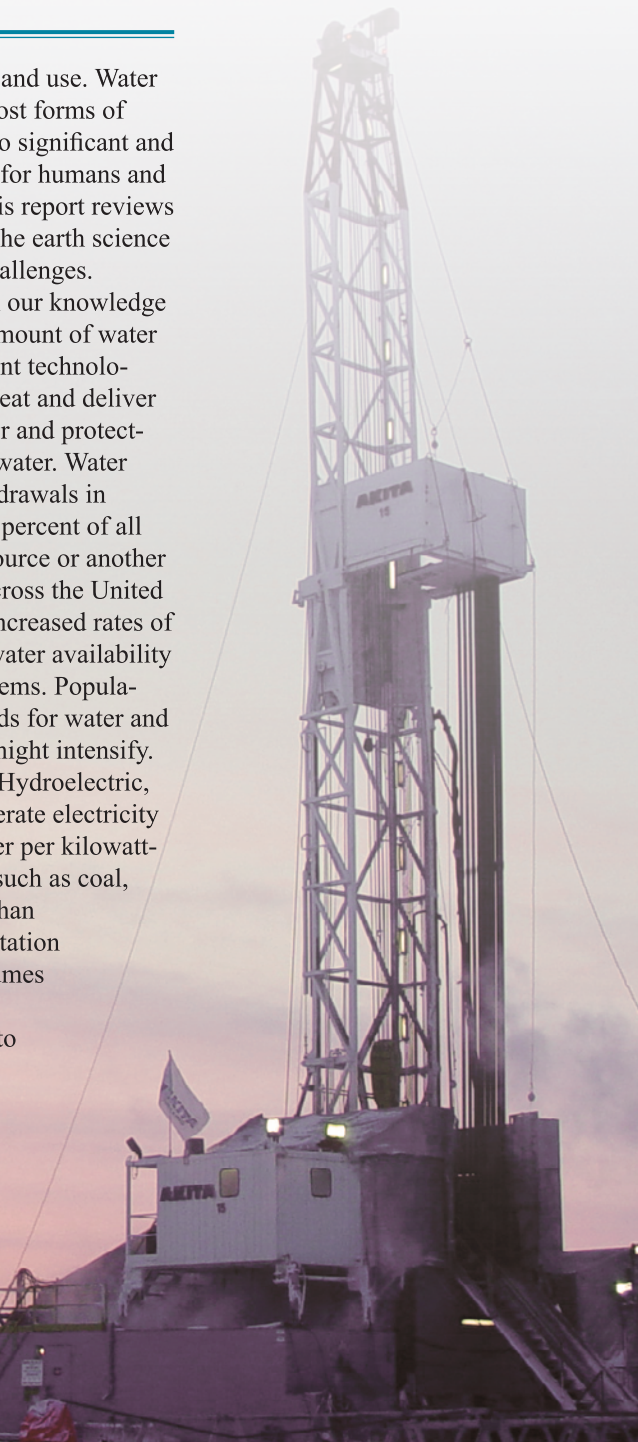
Executive Summary

Water availability and use are closely connected with energy development and use. Water cannot be delivered to homes, businesses, and industries without energy, and most forms of energy development require large amounts of water. The United States faces two significant and sometimes competing challenges: to provide sustainable supplies of freshwater for humans and ecosystems and to ensure adequate sources of energy for future generations. This report reviews the complex ways in which water and energy are interconnected and describes the earth science data collection and research that can help the Nation address these important challenges.

A full understanding of the water-energy nexus is limited by uncertainty in our knowledge of fundamental issues, such as the quantity of freshwater that is available, the amount of water that is used in energy development, the effects that emerging energy development technologies have on water quality and quantity, and the amount of energy required to treat and deliver freshwater. Nevertheless, some findings are clear: reducing the use of freshwater and protecting it from contamination conserve energy, and reducing energy use conserves water. Water withdrawn for energy-related operations represents about 45 percent of all withdrawals in the United States; water consumption for these operations represents about 2–5 percent of all withdrawals. Withdrawn water that is not consumed is returned to its original source or another water body. Water resources and energy operations are not evenly distributed across the United States. In arid and semiarid western regions, freshwater resources are limited. Increased rates of extraction of oil and natural gas in some of these regions raise concerns about water availability for traditional agricultural, municipal, and domestic water users and for ecosystems. Populations are predicted to grow in these western areas in coming decades, so demands for water and energy will likely increase, and competition for limited supplies of freshwater might intensify.

Electricity generation accounts for most energy-related water withdrawal. Hydroelectric, geothermal, and concentrating solar power plants use renewable sources to generate electricity with low carbon emissions; however, these plants generally consume more water per kilowatt-hour of generated electricity than power plants that use nonrenewable sources, such as coal, natural gas, and nuclear power. Production of biofuels is more water intensive than production of hydrocarbon fuels—biofuels make up about 5 percent of transportation fuels in the United States, yet irrigation of crops used to make those fuels consumes as much as one half of the total amount of water consumed in production of all transportation fuels. Energy use for development of water resources is difficult to quantify, but heating water for washing and cooking is estimated to account for more than 70 percent of the total amount of energy used to withdraw, treat, and convey water to and from homes and commercial establishments.



Mallik gas hydrate production test research project.

Decisions on development of water and energy resources are complicated by a number of tradeoffs, including

- the reduced greenhouse gas emissions from some renewable energy sources versus the added amount of water required to develop these sources,
- the improved air and water quality from implementation of carbon capture and geologic sequestration versus the additional fuel and water required for that implementation,
- the reduced amount of water needed for dry-cooled thermoelectric power plants versus the higher fuel requirements for these systems during hot summer months, and
- the large increase in recoverable oil and natural gas reserves brought on by technologies such as directional drilling and hydraulic fracturing versus the unknown environmental costs of the technologies.

The benefits and costs of tradeoffs such as these need to be weighed, but coordinated planning among energy developers, water developers, water-resource managers, and ecosystems managers can result in mutual benefits.

The earth sciences have been a cornerstone in developing our current understanding of the water-energy nexus. Continued data collection and research can reduce the uncertainty that limits our knowledge of many important water-energy issues and thereby lay the groundwork for informed resource management. Relevant earth science issues analyzed and discussed herein include freshwater availability; water use; ecosystems health; assessment of saline water resources; assessment of fossil-fuel, uranium, and geothermal resources; subsurface injection of wastewater and carbon dioxide and induced seismicity; climate change and its effect on water availability and energy production; byproducts and waste streams of energy development; emerging energy-development technologies; and energy for water treatment and delivery.

The intent of this report is to provide scientific insight to resource managers and the general public on the complex ways in which water and energy are interconnected and to highlight the important issues that affect availability and sustainability of water and energy resources in the United States. The goals of preserving sustainable supplies of freshwater for humans and ecosystems and ensuring sufficient energy resources for future generations are not mutually exclusive, but prudent resource management is required to attain them; the earth sciences provide the basis for informed resource-management decisions.

Livestock well with solar-powered pump.

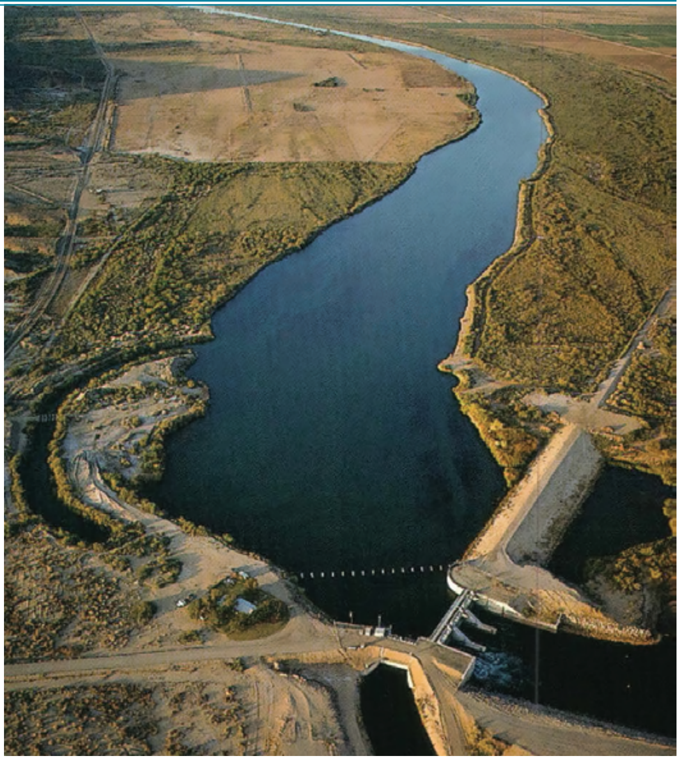
Introduction

Water and energy are essential to human existence. Humans need water to drink, to grow crops, to extract fuels and minerals, to generate power, and to manufacture goods; we embrace water for its aesthetic values and recreational opportunities; and the health of ecosystems depends on the availability of water. Likewise, energy harnessed for human use from conversion of resources such as coal, oil, natural gas, uranium, water, wind, and the sun provides more than mere conveniences. The produced energy sustains a large, vibrant civilization that supports living environments, food production, industry, science, commerce, transportation, entertainment, and much more. Americans have become heavily reliant on the availability of affordable power.

Water and energy resources are intrinsically linked in many important ways. Energy is required to withdraw water, to treat water for human consumption, and to transport water. At the same time, water is required to extract and process fossil fuels, to grow biofuels, and to cool thermoelectric power plants. The availability and economic feasibility of developing either water or energy resources depends largely on the availability and cost of the other resource. Limits on available water may preclude development of some energy resources, just as a lack of electrical power may hinder capabilities to extract, treat, and transport water. A detailed examination of the links between water and energy can enhance capabilities of resource managers to provide freshwater for people and ecosystems and to ensure sufficient power to support human lifestyles. Such an examination can also generate greater public awareness of issues that affect the availability of water and energy resources.

The United States is relatively rich in water and energy resources, but they are not evenly distributed across the country. In regions where available supplies of water are limited, there is a long history of competition for that water among traditional agricultural, municipal, industrial, and energy interests (Reisner, 1993). This competition might increase as populations grow, extraction of oil and natural gas increases, and the effects of energy development on water quantity and quality become more apparent. Prospects for avoiding future water and energy conflicts may be improved if there is an appreciation on the part of all interested parties of the limited availability of water and fossil fuels and the interdependence of water development and energy development.

This report provides an overview of the important ways in which water and energy are interconnected. The report is aimed primarily toward water- and energy-resource managers in the United States; however, the material is presented in a way that will appeal to large segments of the general public. The objective of this report is to provide readers with scientific insight to the challenges to be overcome as Americans strive to develop a sustainable supply of freshwater for humans and ecosystems while at the same time ensuring the availability of energy resources for future generations. These are complex challenges, and to address them in a comprehensive manner requires the consideration of economic, human-health, cultural, and societal issues. But key to any analysis of the water-energy nexus is a firm understanding of fundamental earth science issues, including the availability of water and energy resources; the extraction, processing, and conservation of these resources; and the protection of water resources for humans and ecosystems.



Dam and reservoir.

The section “Water in Energy Production and Use” describes and explains the water needs for energy production and use along with associated water-quality issues. The amount of water required to deliver a kilowatthour (kWh) of electricity to a home is calculated for all steps from fuel extraction and processing, through generation and delivery of electricity, to final disposal of byproducts. The section “Energy for Water Development, Distribution, and Use” presents an analysis of the energy requirements for withdrawing, treating, and delivering water; energy use is given in terms of kilowatt-hours per liter of water. The analyses in these two sections facilitate comparison of the costs (in terms of water) for different types of energy production, as well as the cost (in terms of energy) for withdrawing, treating, and delivering water. The section “Science for Addressing the Water-Energy Nexus” contains a discussion of the role that the earth sciences play in addressing the important interrelated energy and water issues.

Continued on page 6

A Energy Consumption in the United States

Working with numbers for energy production can be confusing because the volume, mass, and energy content of individual fuels are often reported in unique sets of units. Oil volume is reported in barrels, natural gas volume is reported in million cubic feet, and coal mass is reported in tons or metric tons. The International System of Units (SI) is used in this report, and energy is reported in kilowatthours—a unit equivalent to one kilowatt of energy use for a period of one hour. Both electrical energy and thermal energy—the energy content of a fuel—are expressed in kilowatthours. In this report, kilowatthours of electricity use the abbreviation kWh, and kilowatthours of thermal energy use the abbreviation kWh_{th}. Factors for converting energy, volumes, masses, and energy contents to more familiar units are provided in the table on page x.

Annual energy consumption in the United States has followed a general upward trend since 1949, reaching a level estimated to be 28.5 trillion kWh_{th}, or about 90,000 kWh_{th} per person, in 2013 (fig. A–1; U.S. Energy Information Administration, 2014b). The 90,000 kW_{th} are equivalent to the amount of energy contained in 11 metric tons of coal or about 10,000 L of gasoline.

Most of the energy we consume is produced from fossil fuels—oil, natural gas, and coal (fig. A–2). Oil is used primarily for transportation purposes (for example, gas and diesel fuel for cars and buses, and jet fuel for aircraft). Natural gas is used for industrial purposes, for heating residential and commercial buildings, and for generating electric power. Coal is the most widely used fuel for generating electricity, although natural gas, nuclear energy, and renewable energy are also used for this purpose. Renewable energy is used in a wide spectrum of sectors.

For electric power, the numbers in figure A–2 represent the energy consumed by power plants (11.2 trillion kWh_{th}); however, the energy consumed is not equal to the energy (in the form of electricity) that is delivered to an end point. As will be described in subsequent sections, energy losses occur in the production and transmission of electricity. Of the 11.2 trillion kWh_{th} consumed by power plants, only 3.9 trillion kWh of electrical energy were actually delivered to customers; approximately 65 percent of the consumed energy was lost as heat or other forms of energy that are not captured for human use.

A 20-watt light bulb turned on for 1 hour uses 20 watt hours or 0.02 kilowatthours of electricity.

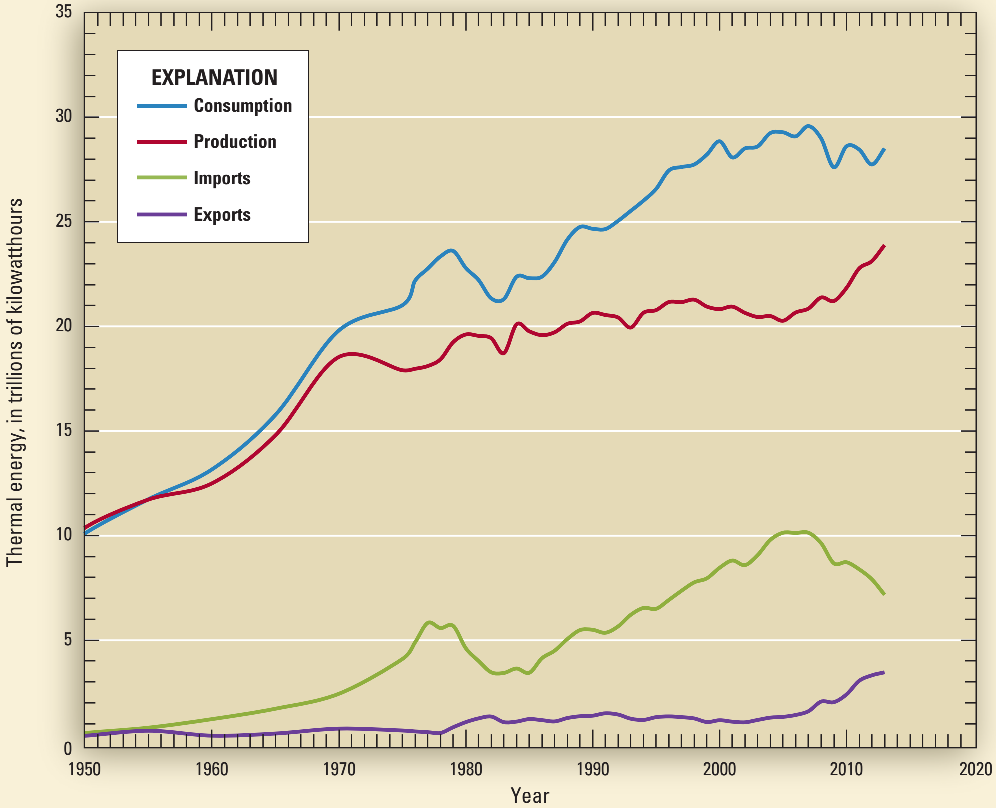


Figure A–1. Total annual energy consumption, production, imports, and exports for the United States, 1950–2013. (U.S. Energy Information Administration, 2014b)

Domestically produced fuels accounted for approximately 75 percent of energy consumption in the United States in 2013; imported fuels accounted for the remaining 25 percent. The reliance of the United States on imported fuels has been in decline since 2006 when imported fuels accounted for 35 percent of total consumption. Imported fuel is primarily oil—net imports accounted for approximately 33 percent of all oil consumed in the United States in 2013, whereas in 2006 they accounted for over 60 percent (U.S. Energy Information Administration, 2014b).

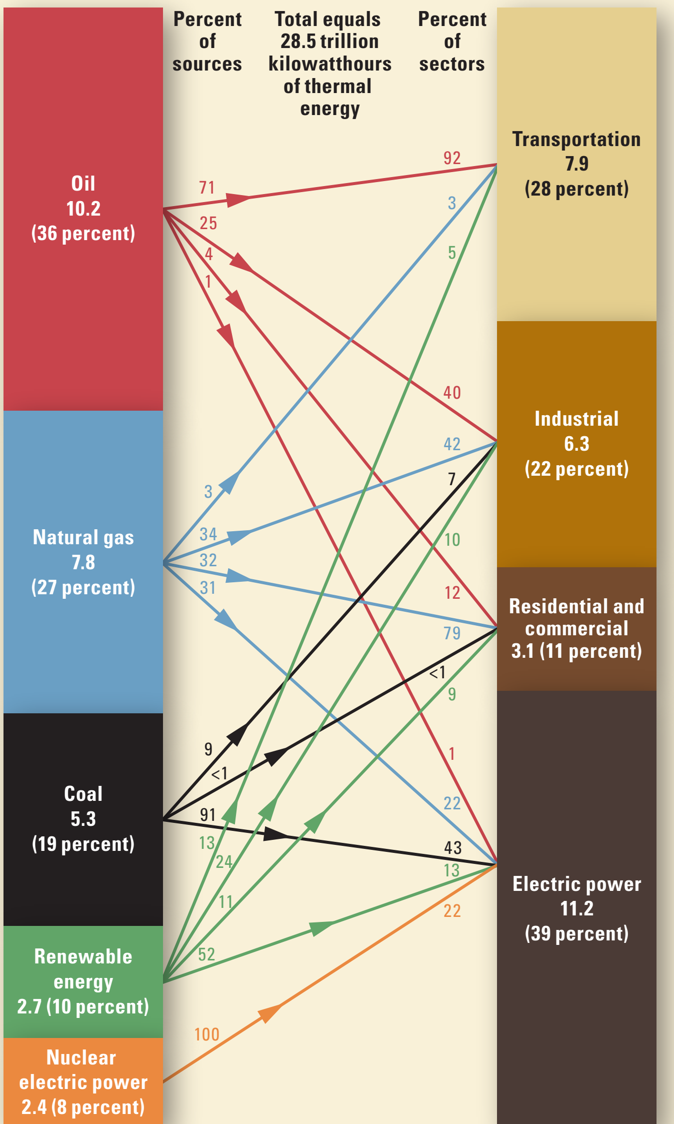
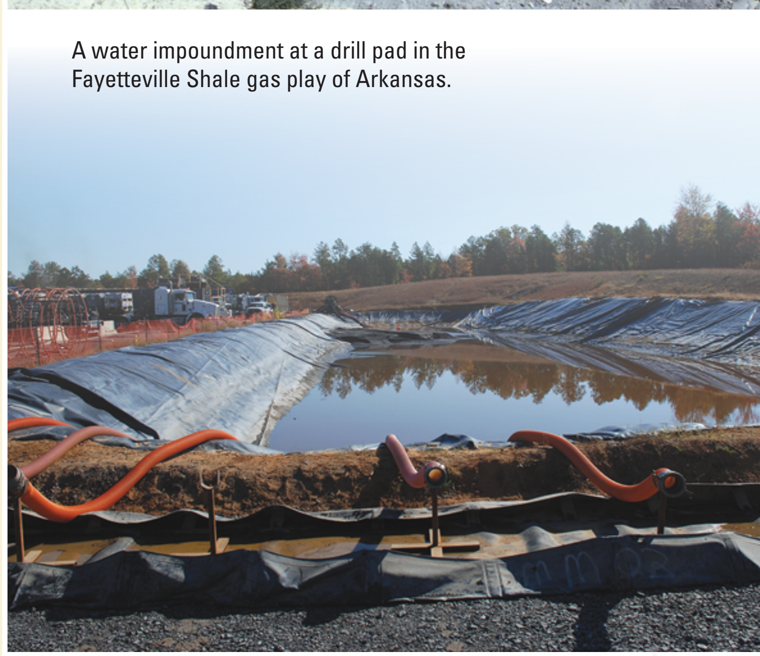


Figure A–2. Estimated energy consumption for the United States by energy source and energy-use sector, 2013, in trillions of kilowatthours of thermal energy. Oil includes natural gas liquids. (U.S. Energy Information Administration, 2014b)

Coal mining operation.



A water impoundment at a drill pad in the Fayetteville Shale gas play of Arkansas.

Fossil fuel extraction.

Water in Energy Production and Use

Water is associated with all steps of energy development, including fuel extraction and processing, generation of electricity, and final end use (fig. 1). The water needs for each of these steps are described within this section; in addition, estimates of total water consumption are summarized for electricity generation and for each of the energy-use sectors as defined by the U.S. Energy Information Administration (2014a): residential, commercial, industrial, and transportation. Water requirements for fuel extraction and processing are provided in terms of the amount of water required for extracting and processing a unit volume or mass of fuel (for example, liters of water per cubic meter of natural gas or liters of water per liter of gasoline). For electricity generation and end use, water-consumption numbers are converted to water intensities: volume of water consumed (in liters) per unit of generated electricity (in kilowatthours). The use of water intensities facilitates the comparison of water consumption rates for different fuels and different energy uses.

The distinction between water withdrawal and water consumption must be clear in the reader's mind. As described in Box B, water withdrawal is the extraction of water from surface-water or groundwater sources, water use refers to water withdrawal for a specific purpose, and water consumption is that part of withdrawn water that is evaporated or removed from the immediate water environment by some other means. These terms are not used consistently in all reports, which can cause confusion and uncertainty. Some reports make no distinction between withdrawal and consumption rates, and some reports provide only consumption rates. For many energy development operations, withdrawal and consumption rates are similar, but for operations at thermoelectric power plants, water consumption rates can be just a small fraction of withdrawal rates.

Water-quality problems can arise in all areas of energy development and use. Water contamination can result from a variety of factors, including improper procedures, faulty infrastructure, weak regulations, and acts of nature. It can occur through direct pathways, such as leaks in pipes or storage tanks and injection of fluids into wells, or through indirect pathways, such as acid-mine drainage from abandoned mine spoils and atmospheric emissions from power plants and motor vehicles.

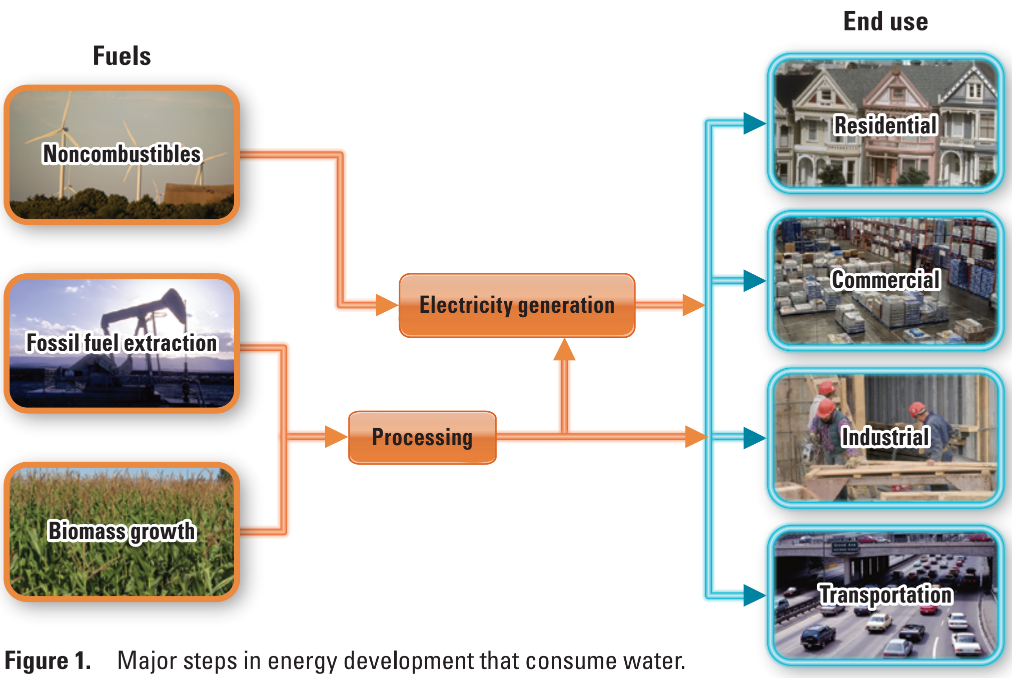


Figure 1. Major steps in energy development that consume water.

Fuel Extraction and Processing

The energy that Americans consume comes from a number of different fuels and natural resources. Electricity is generated from coal, natural gas, and uranium and from flowing water, geothermal heat, wind, and the sun. Homes and businesses are heated by natural gas, electricity, wood, fuel oil, and coal. Motor vehicles are powered by hydrocarbon fuels and biofuels and increasingly by electricity. Water is involved in virtually every step of extracting, growing, and processing these fuels. Water use and associated water-quality issues associated with fuel sources—natural gas, oil, coal, uranium, and biomass—are described in the following sections. (See the section "Electrical Power Generation" for discussions on thermoelectric, hydroelectric, wind and solar sources.)

Natural Gas and Oil

Natural gas and oil together account for more than 60 percent of all energy consumption in the United States on an annual basis. We group oil and natural gas together in this section because they are related geologically and because techniques for extracting the two are similar. In 2013, the United States consumed about 0.95 trillion liters (L) of oil (U.S. Energy Information Administration, 2014b), equivalent

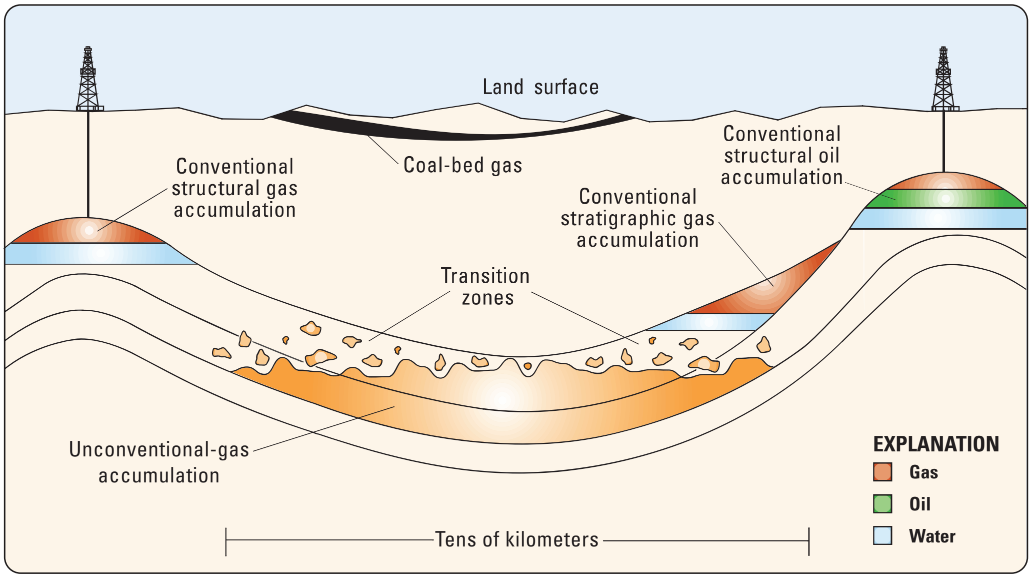


Figure 2. Categories of conventional and unconventional hydrocarbon occurrences. (From Schenk and Pollastro, 2002)

to 10.2 trillion kilowatthours of thermal energy.[1] Most oil is used for transportation fuels—gasoline, diesel fuel, and jet fuel—with smaller amounts used for industry, home heating, and generation of electricity. Natural gas consumption in 2013 was about 740 billion m^3, or about 7.8 trillion kWh_{th} of energy (U.S. Energy Information Administration, 2014b). Natural gas is used for heating residential and commercial buildings, heating water, industrial purposes, and generation of electricity.

Natural gas and oil resources typically are categorized into two broad groups: conventional and unconventional resources (Schenk and Pollastra, 2002). Conventional resources refer to oil and natural gas that have migrated from a source rock into a discrete geological trap where a well-defined water-hydrocarbon contact exists (fig. 2). By comparison, unconventional hydrocarbon resources, also referred to as continuous resources, consist of oil and natural gas dispersed through one or more geologic layers with no obvious water-hydrocarbon contact. Examples of unconventional resources include shale gas; coalbed natural gas; gas in low-permeability sandstones, siltstones, and carbonates (referred to as tight gas); oil in low-permeability sandstones and shales (referred to as tight oil); oil shale; and oil sands.

Domestic production of both natural gas and oil has increased steadily since 2005 (fig. 3), and that trend is expected to continue (U.S. Energy Information Administration, 2012b). The increased productivity is from unconventional sources and is the direct result of better geologic understanding of these resources and advanced techniques employed by the energy industry. The two most important of these techniques are directional well drilling and hydraulic fracturing (fracking). Directional drilling allows wells to extend several kilometers horizontally within an oil or gas reservoir and to intercept multiple discrete production zones. In addition, several wells can be drilled in different directions from a single well pad, thus minimizing infrastructure requirements and surface footprints. Hydraulic fracturing is a method

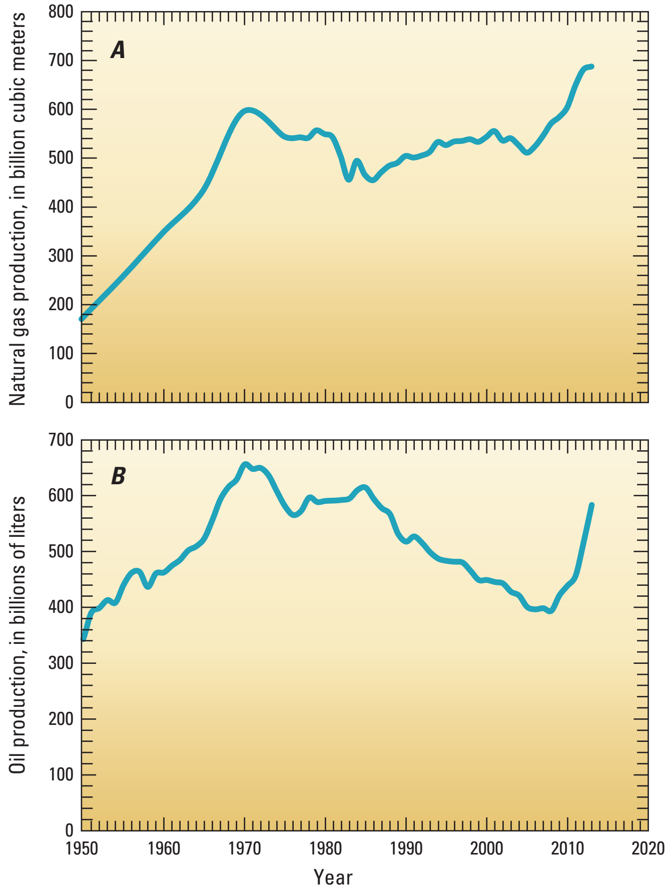


Figure 3. Annual domestic production of (*A*) natural gas and (*B*) oil (including natural gas plant liquids) in the United States, 1950–2013. (U.S. Energy Information Administration, 2014b)

[1]Thermal energy refers to the energy content of the fuel, as opposed to electrical energy generated from consuming that fuel, which is also expressed in terms of kilowatthours; for clarity in notation throughout the remainder of the report the term kWh_{th} is used to represent kilowatthours of thermal energy, and the term kWh is used to represent kilowatthours of electrical energy.

for enhancing the permeability of the reservoir rock by applying high pressure to isolated sections of the well bore to create fractures in the rock (see Box C—Hydraulic Fracturing). Together, these techniques have made it possible to capture oil and natural gas contained in shale and sandstone formations that cover vast swaths of the United States (fig. 4). In the past, those resources were considered largely inaccessible.

Water is involved in all stages of natural gas and oil development, including exploration, production, and processing. Some stages require minimum amounts of water; others require substantial quantities—hydraulic fracturing of a single well may require millions of liters of water. In addition, water often is extracted along with oil and natural gas; this water is referred to as produced water, and it can consist of native water present in the geologic formation prior to development and fluids and chemicals injected into the formation to stimulate production. Water requirements and the quantity and quality of produced water in oil and natural gas development are affected by a number of factors, including the type of energy resource being developed, the local and regional geology and hydrology, and the processes that are used in development. As will be discussed in subsequent sections, a shortage of quantitative data and the large variability in natural conditions across the United States lead to a substantial uncertainty in estimates of water requirements for development of oil and natural gas. Water-quantity and quality issues associated with exploration, production, and processing of natural gas and oil are addressed in the following sections.

Source: Energy Information Administration, based on data from various published studies, updated May 9, 2011

EXPLANATION

Shale plays
- Current play
- Prospective play
- **Pearsall** **Shale play name**

Stacked plays
- Shallowest/youngest
- Intermediate depth/age
- Deepest/oldest

TX-LA-MS Salt Basin — **Basin and name**

Figure 4. Shale plays of the conterminous United States. (U.S. Energy Information Administration, 2011)

Water Use

Natural Gas

Water is a key ingredient in drilling fluids. These fluids serve multiple purposes in well drilling, including floating crushed rock and sediment from the drill bit to land surface, lowering friction between the drill bit and rock, and cooling moving parts in drilling systems. Estimates of the volume of water required for drilling a well vary widely and depend on the well length, diameter, and amount of water loss to the surrounding formations. Conventional onshore vertical gas wells generally require negligible amounts of water for drilling and gas extraction (International Energy Agency, 2012b). Horizontal shale gas wells that extend several kilometers typically require more water than vertical wells for drilling, but the amount of water used for drilling is still small relative to that for well stimulation (Nicot and Scanlon, 2012).

Extraction of shale gas and tight gas usually requires some kind of fracture stimulation. Several techniques for inducing fractures can be used, but water-intensive hydraulic fracturing is probably the most common technique (see Box C—Hydraulic Fracturing). Water requirements for hydraulic fracturing vary depending on geology and well design. One operator reports a range of 0.1 to 0.2 liters of water per cubic meter of natural gas (L-water/m^3–natural gas) for drilling and hydraulic water fracturing of four major shale gas plays (Haynesville, Marcellus, Barnett, and Fayetteville; fig. 4.); in addition, up to 0.3 L of water may be needed for processing each cubic meter of natural gas in order to remove gas liquids, mercury, hydrogen sulfide, and other impurities (Mantell, 2010). These estimates are consistent with the range in water consumption provided by the International Energy Agency (2012b) (table 1). Coalbed natural gas, though considered an unconventional resource, often does not require hydraulic fracturing for its extraction, so water requirements for producing coalbed natural gas are generally less than those for other unconventional gas reservoirs.

Continued on page 15

Table 1. Water consumption for different steps in production of natural gas, oil, coal, and uranium.

[--, no data; EOR, enhanced oil recovery]

	Hydraulic fracturing	Processing/refining	Total production
Natural gas, in liters of water per cubic meter of gas			
Conventional	--	[5]0.3	[1]0.004–0.04
Conventional with fracturing	--	[5]0.3	[1]0.02–0.19
Tight gas	[5]0.1–0.2	[5]0.3	[1]0.04–0.38
Shale gas	[5]0.1–0.2	[5]0.3	[1]0.08–3.8
Oil, in liters of water per liter of oil			
Conventional	--	[1,2]0.19–1.4	[1]0.04–1.9
Conventional with fracturing	--	[1,2]0.19–1.4	[1]0.19–1.9
Conventional—primary	--	[1,2]0.19–1.4	[1]0.2
Conventional—secondary	--	[1,2]0.19–1.4	[2]8.6
Conventional—EOR	--	[1,2]0.19–1.4	[2,3]1.9–13
Tight oil	--	[1,2]0.19–1.4	[1]0.19–3.8
Shale oil	--	[1,2]0.19–1.4	--
Oil sands	--	[1,2]0.19–1.4	[4]0.4–5.8
Oil shale	--	[1,2]0.19–1.4	[6]0. 8–11.8
Coal, in liters of water per metric ton of coal			
Conventional surface/underground	--	--	[3,7,8]75–500
Uranium, in liters or water per kilogram of enriched uranium			
Conventional	--	[3,9]9,600–16,500	[3,9]9,600–16,500
Solution mining	--	[3,9]51,600–56,500	[3,9]51,600–56,500

[1]International Energy Agency (2012b).
[2]Wu and others (2009); Wu and Chiu (2011).
[3]Gleick (1994).
[4]Moorhouse and others (2010).
[5]Mantell (2010).
[6]U.S. Government Accountability Office (2010).
[7]Pate and others (2007).
[8]Nicot and others (2011).
[9]Mudd and Diesendorf (2008).

B Water Availability and Usage in the United States

Water Availability

Water availability is a somewhat nebulous term. The water volume within a hydrologic system and the rates of water movement through that system can be measured or estimated (albeit with some degree of uncertainty). Such quantification is integral to the concept of water availability, but the concept extends beyond merely knowing volumes and rates of water flow. The amount of water that is available for a particular use is dependent on many other factors—including the quality of the water; the intended use of the water; laws and regulations that govern water ownership and use; the physical nature of the hydrologic system; the ecosystems, culture, lifestyles, and societal values of the region; and the economic aspects of water development—and these factors vary from region to region. They also vary over time as economic, climatic, hydrologic, and environmental conditions change. As such, water availability is best determined on a region-by-region basis with periodic reassessments over time. As of 2014, no quantitative assessment of water availability has been completed at the national level, though such assessments at the state and watershed level are common and are often key components of water-management strategies. As directed by the United States Congress, the U.S. Geological Survey is currently (2014) working with other Federal and State agencies to conduct a nation-wide water census that will provide an assessment of the status and trends in freshwater availability and use (Alley and others, 2013).

Quantification of water resources is commonly done in the context of a hydrologic or water budget (Healy and others, 2007). A water budget describes the movement of water into, through, and out of a representative volume, such as a watershed, a state, or the country as whole. A simple water-budget equation for a watershed is given by:

$$P + Q_{in} = ET + \Delta S + Q_{out},$$

where

- P is precipitation,
- Q_{in} is surface and subsurface flow into the watershed,
- ET is evapotranspirzation,
- ΔS is change in water storage, and
- Q_{out} is surface and subsurface flow out of the watershed (including human withdrawals).

The equation states that water entering the watershed (through precipitation or surface and subsurface flow) is lost to evapotranspiration, flows out of the volume, or adds to water storage in the watershed (fig. B–1).

Although it is difficult to quantify, water storage is a key metric for determining sustainable water use—continuous decreases in water storage will eventually result in decreased availability for humans and the environment. Surface features such as lakes, wetlands, and to a lesser extent rivers and streams are the most prominent visual expressions of water storage; however, the vast majority of freshwater in the United States is found in the subsurface soil water and groundwater (Healy and others, 2007). Accurate assessment of subsurface water resources is one of the more challenging aspects of efforts to quantify available water.

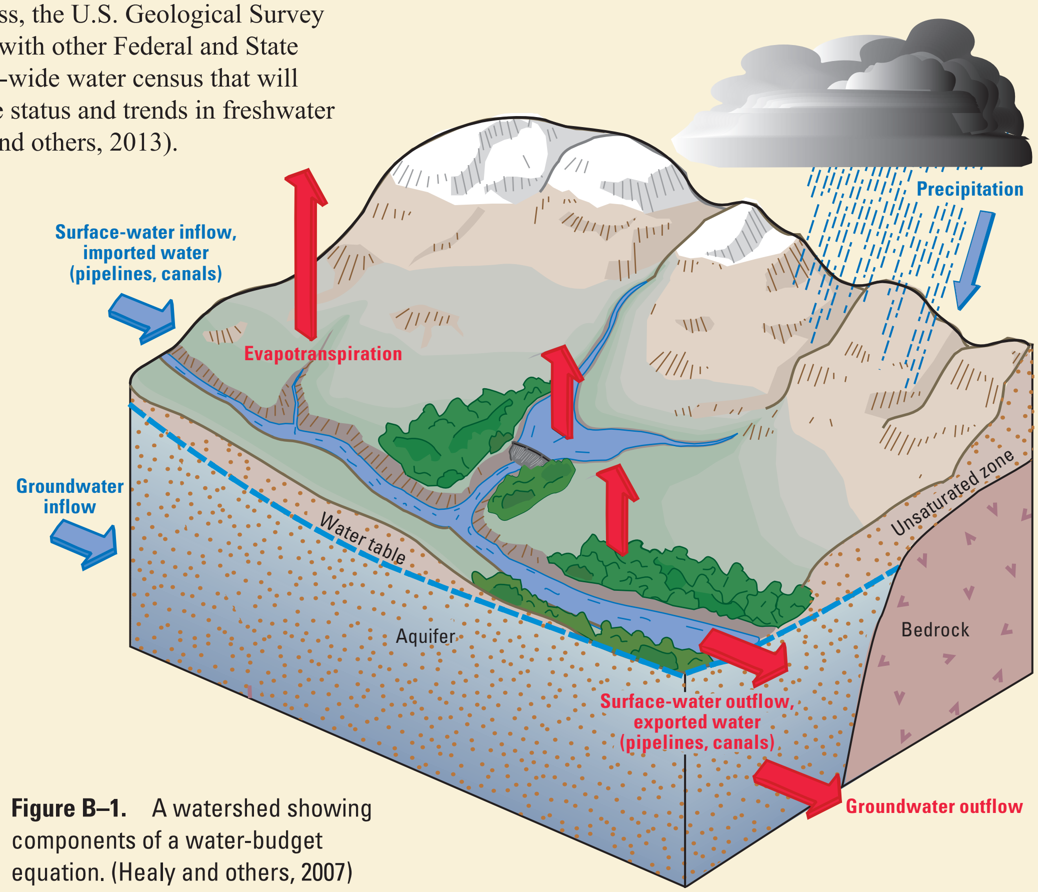


Figure B–1. A watershed showing components of a water-budget equation. (Healy and others, 2007)

With an average annual precipitation of 767 mm, the United States is often thought to have an abundance of freshwater, but water is not evenly distributed across the country. Annual rates of precipitation range from less than 100 mm in Death Valley, California, to more than 7,000 mm in parts of Hawaii and the Olympic Peninsula of Washington (fig. B–2). Vast regions of the western United States have arid or semiarid climates; these regions also hold substantial fossil-fuel resources. Conflicts among water users are woven throughout the history of these western regions. Competition for limited water supplies in these regions will likely increase with growing populations and increased demands for energy.

Water Use

Clarification of terminology used in this report will help to avoid ambiguity and confusion. Water withdrawal is defined as water removed from the ground or diverted from a surface-water source for use. Water use refers to withdrawal of water for a specific purpose (for example, water supply or irrigation). Water consumption (sometimes referred to as consumptive use) is that part of withdrawn water that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment. Depending on category of water use, consumption might be a large percentage of withdrawal, as with irrigation, for example, or only a small part of withdrawal, as with thermoelectric power plants that use once-through cooling systems. Most of the water withdrawn for irrigation is transferred to the atmosphere through evapotranspiration. In once-through cooling systems, most of the water withdrawn for cooling is returned to the original supply source; power plants with these systems withdraw large volumes of water, but they usually consume only small amounts of that water. Nonconsumptive water use, however, can still affect water availability—any human activity, including the development of energy resources, has the potential to degrade water quality, thereby reducing the amount of freshwater available for other uses.

Quantifying water usage in the United States is a difficult task, but it is a more tractable endeavor than quantifying water availability. The U.S. Geological Survey publishes estimates of water withdrawal for the Nation on a 5-year cycle for 8 categories of water use: public supply, rural domestic supply, irrigation, livestock, industrial, aquaculture, mining, and thermoelectric power. Thermoelectric power plants withdraw the largest share of water, followed by irrigation, and public water supply (fig. B–3).

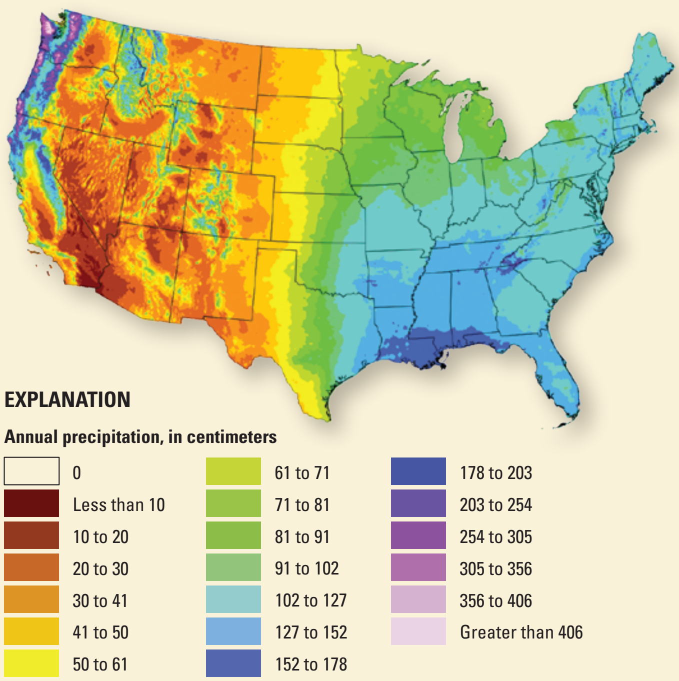


Figure B–2. Average annual precipitation in the conterminous United States, 1981–2010, as determined with the PRISM dataset (*http://prism.oregonstate.edu/normal/*, PRISM Climate Group, Oregon State University).

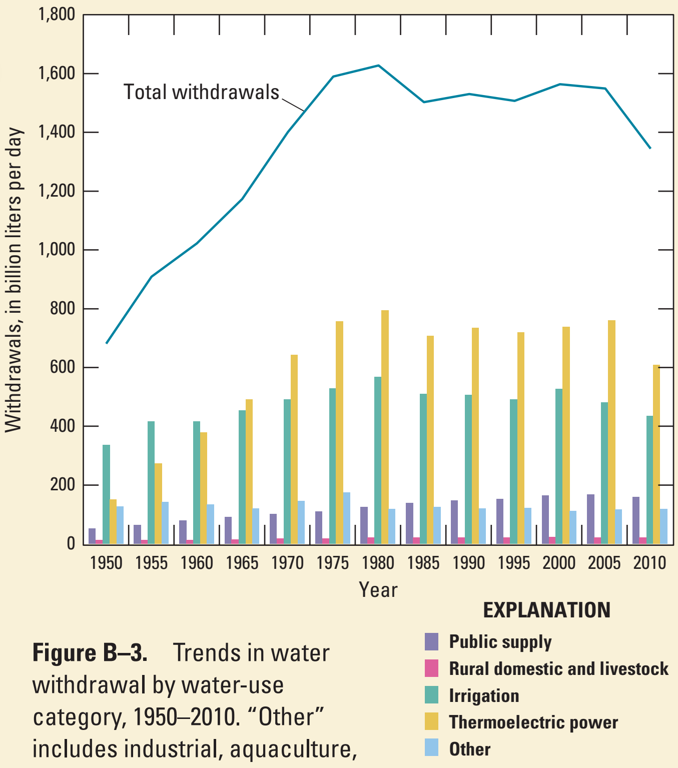


Figure B–3. Trends in water withdrawal by water-use category, 1950–2010. "Other" includes industrial, aquaculture, and mining. (Maupin and others, 2014)

C Hydraulic Fracturing

Hydraulic fracturing, or "fracking"—few terms arouse as much passion on the part of the public and energy developers. To many, the term signals the destruction of pristine aquifers that supply drinking water to more than half of the population of the United States. Others cheer the facts that hydraulic fracturing and related advances in well drilling have led to improved national energy security and reduced energy costs. So what is the reality of the situation? The truth is that there are many issues to consider. In this section, we briefly describe the process of hydraulic fracturing, highlight the benefits it provides, and discuss its potential unintended consequences in regard to water resources.

In many parts of the United States, natural gas and oil exist in low-permeability rocks such as shales and tight sandstones. Until recently, extraction of these resources has not been economically feasible because of that low permeability. The process of hydraulic fracturing involves injection of fluids into a well under pressures high enough to fracture the host rock, thereby increasing the permeability of the rock and facilitating the extraction of the hydrocarbon resource. Hydraulic fracturing, technologies such as directional drilling, which can align a well parallel to reservoir dip (fig. C–1), and drill rigs that can efficiently drill multiple wells from a single drill pad all have substantially enhanced the ability to develop low-permeability hydrocarbon reservoirs. As a result, annual estimates of U.S. natural gas reserves have risen dramatically since the mid-1990s (fig. C–2).

Demonstrators rallying against fracking.

Fracturing of reservoirs has been used for decades to enhance productivity of oil, gas, and even drinking water wells. Various fluid mixtures can be used in the procedure. The most commonly used fracturing fluids for gas and oil wells in shales and tight sands are referred to as slickwater fluids; water, gels, foams, propane, and kerosene have also been used as fracturing fluids. Slickwater consists of about 87 percent water, 11 percent sand, and 2 percent chemical additives (fig. C–3; Groundwater Protection Council and ALL Consulting, 2009; National Energy Technology Laboratory, 2013). Sand or ceramic beads are added to prop fractures open, and the chemical additives are designed to facilitate flow from the reservoir by reducing friction and inhibiting the formation of scale and microbial films. Additives can include acids, surfactants, biocides, and friction reducers (fig. C–3).

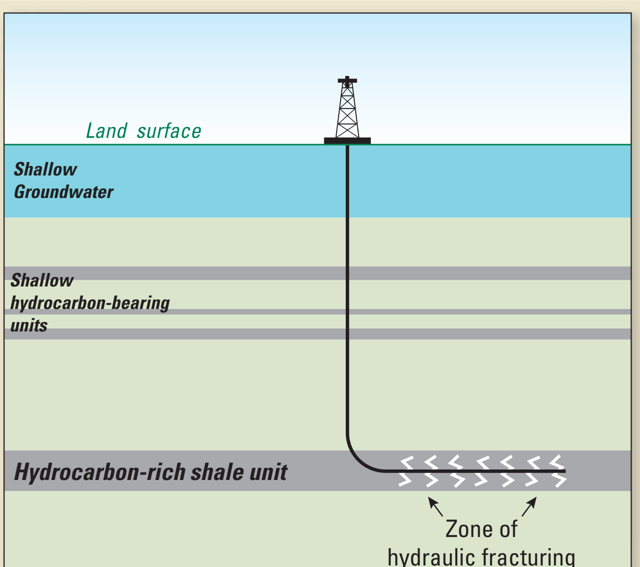


Figure C–1. Cross-section view of a hydraulically fractured shale gas well. (Modified from Soeder and Kappel, 2009)

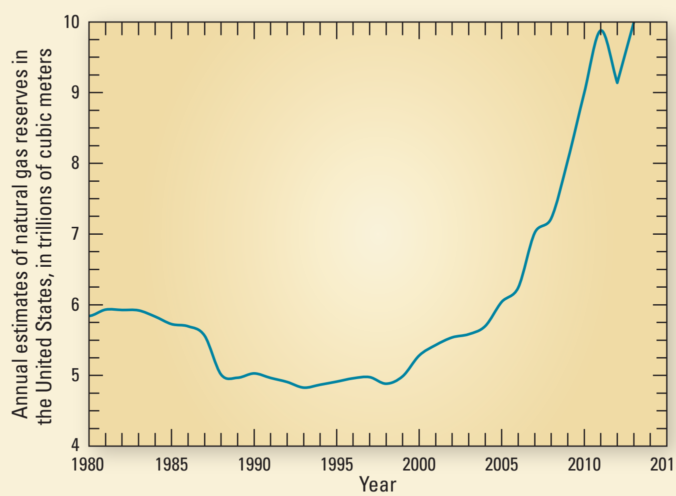


Figure C–2. Annual estimates of natural gas reserves in the United States, 1980–2012. Estimated reserves have nearly doubled since the mid-1990s, largely because techniques like hydraulic fracturing allow gas to be captured from new unconventional reservoirs. (U.S. Energy Information Administration, 2013c)

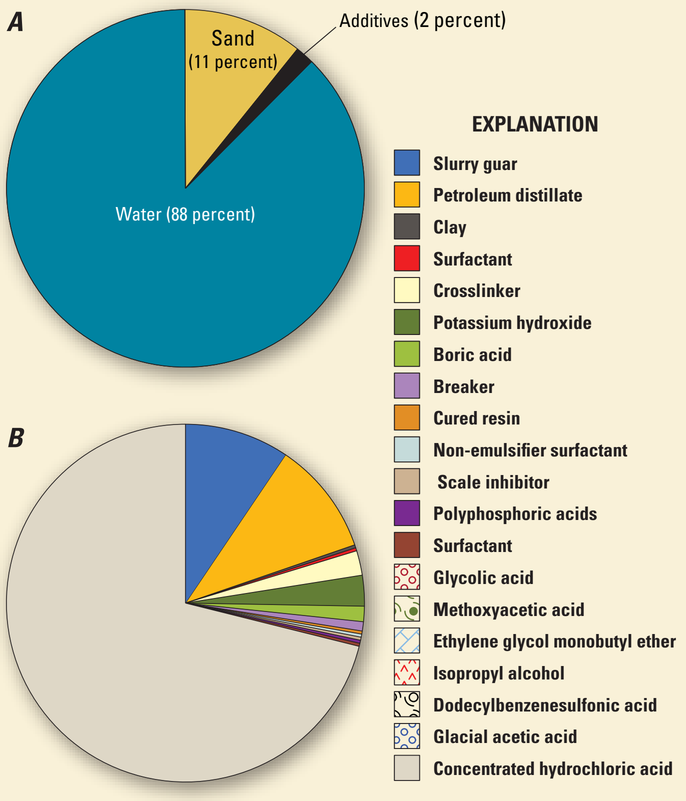


Figure C–3. Relative volume of the various materials used to hydraulically fracture an oil well in the Texas portion of the Permian Basin, from a total volume of 4.5 million liters (data from *fracfocus.org*). *A*, Relative volumes of water, sand, and additives used. *B*, relative volume of the specific additives used.

The fluid mixture is injected into the reservoir under pressures that exceed the strength of the host rock, producing a series of fractures in that rock. After a period of time, ranging from hours to weeks, pressure is removed from the system, and extraction of hydrocarbon product begins. Hydraulic fracturing commonly consists of a series of stimulations over different intervals of the well, with the process usually initiating at the far end of a well and stimulations gradually progressing back up the well (Groundwater Protection Council and All Consulting, 2009). The volume of water required for hydraulic fracturing is highly variable and depends on the hydraulic properties of the reservoir, the dimensions of the well, and the specific techniques applied. Median values of water use in the Barnett, Haynesville, and Eagle Ford Shales in Texas were estimated at 9,500–14,000 L per meter of linear distance of fractured well casing (Nicot and Scanlon, 2012). Accordingly, the hydraulic fracturing of a 3,500-m-long horizontal well could require up to 49 million L of water.

Upon completion of the fracturing procedure, pumping is initiated to extract the hydrocarbons. Water is also extracted with the hydrocarbons. Some of this produced water is injection water and some is native formation water. The produced water can be reused in some cases; otherwise, the water is typically disposed of by deep subsurface injection or by delivery to a water-treatment plant. A large portion, in some cases in excess of 90 percent, of the injected fluid is never recovered from the reservoir. This is particularly true for shale-rich units (Groundwater Protection Council and ALL Consulting, 2009; National Energy Technology Laboratory, 2013). In addition to water retained in the artificially developed fractures, water is often lost to the reservoir through a process called imbibition, in which injected fluids replace hydrocarbons that were originally stored in very small pores in the reservoir rock. Shales typically have a much larger percentage of these very small pores than do sandstones, which might explain the relatively higher water loss noted for wells in shale relative to those in sandstone (Byrnes, 2011).

Most public concerns regarding hydraulic fracturing are centered on three issues: contamination of streams and shallow freshwater aquifers, the disposition of produced waters, and the potential for inducing earthquakes or other seismic activities. These issues are addressed individually in the following paragraphs.

Streams and shallow aquifers can be contaminated by liquid spills or leaks that occur on the land surface; spilled contaminants can include drilling fluids, fracturing fluids, and fuels used by machinery involved in well drilling and development (Kappel and others, 2013). Streams and ecosystems can also be adversely affected by sediment released during the construction of roads and pipelines that are needed for new wells. Surface contamination is not specific to wells that undergo hydraulic fracturing; it is a concern with all oil and natural-gas operations. Shallow aquifers also can be affected if hydrocarbons, fracturing fluids, or deep brines are transported upward from the hydrocarbon reservoir. Shallow aquifers and deep reservoirs are typically separated by hundreds or thousands of meters of low-permeability rocks that serve as a natural barrier to that transport (fig. C–4). The composite thickness and permeability of these intervening rocks and the differences in fluid pressures between the shallow and deep systems govern fluid movement. The permeability of these “confining” layers could potentially be enhanced by the fracturing procedure; however, after analyzing data from thousands of hydraulic fracturing operations in the Marcellus, Barnett, Woodford, Eagle Ford, and Niobrara Shales, Davies and others (2012) concluded that the probability of a stimulated fracture extending more than 350 m was very low, about 1 percent. The maximum height of fractures measured in that study was 588 m; the minimum depth interval between the bottom of shallow

C Hydraulic Fracturing—Continued

freshwater aquifers and the top of the fractured zone was about 800 m for these systems. In a separate study, Jackson and others (2013) suggested that the contamination of shallow aquifers by fluid movement upward through fractures created by hydraulic fracturing has a low probability. As of 2013, no confirmed cases of such aquifer contamination have been documented in the United States; however, cases of suspected contamination are being investigated in Texas, Wyoming, and Pennsylvania (U.S. Environmental Protection Agency, 2011b). Compromised well casings, such as those inadequately sealed with cement grout, can also serve as avenues for the migration of methane and saline water to shallow aquifers (Ide and others, 2006); as with surface contamination, this is a concern for all oil and natural gas wells.

The treatment of produced waters can be problematic, both in terms of water quantity and quality. In addition to the chemicals added to fracturing fluids, naturally occurring contaminants in the deep reservoir can be mobilized and dissolved in these fluids. These contaminants can include radium-226 and radium-228 as well as multiple volatile organic compounds and salts. Municipal wastewater treatment plants were not originally designed to treat large volumes of saline fluids. Some plants in rural Pennsylvania, for example, were completely overwhelmed. As a result, private facilities were established specifically for treating produced water, and the reuse of produced water was expanded (Schmidt, 2013).

Hydraulic fracturing can induce small earthquakes of moment magnitude less than 1, but according to recent reports, hydraulic fracturing does not pose a high risk for inducing seismic activities that can be felt (National Research Council, 2012; Ellsworth, 2013). ("Felt" earthquakes are typically those with magnitudes of 2 or greater.) From 2005 through 2012, thousands of wells were hydraulically fractured in Pennsylvania, but only 6 earthquakes with magnitudes of 2 or greater were detected within the footprint of the Marcellus Shale (Ellsworth, 2013), the largest having a magnitude of 2.3. A magnitude 2.9 earthquake in south central Oklahoma might have been related to hydraulic fracturing, but seismic data were insufficient to conclusively rule out other causes. Injection of wastewater is a more common cause of felt earthquakes than hydraulic fracturing (see Box H—Subsurface Fluid Injection), although injection-induced earthquakes are still rare (Ellsworth, 2013).

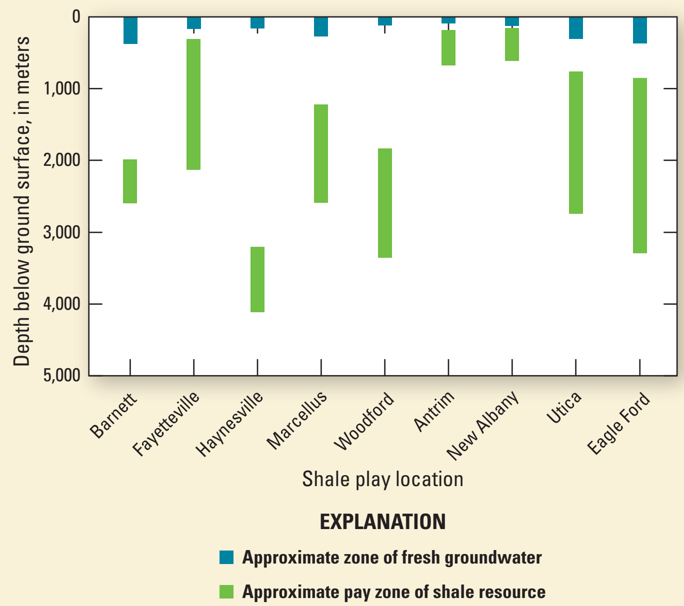


Figure C–4. Approximate depth of zones of shallow, fresh groundwater sources (blue) relative to reservoir depths for important shale gas reservoirs (green) of the United States. Deeper shales, such as the Haynesville and Woodford, have a greater natural buffer for restricting fluid migration upward. Locations of gas reservoirs are shown in figure 4. (Data from National Energy Technology Laboratory, 2013)

Bakken drilling and completion activities at a well along Interstate-94, 6 miles east of Belfield, North Dakota, 2013.

Increased natural gas production from shale and other tight reservoirs in recent years has led to concerns over water availability. Nicot and Scanlon (2012) estimated that net water use for hydraulic fracturing of tight-gas and shale-gas reservoirs in Texas would increase from 46 billion liters of water per year (L/yr) in 2012 to 179 billion L/yr by the mid-2020s. At the same time, operators are expanding their reuse of produced waters and other wastewaters to minimize freshwater use (Curtright and Giglio, 2012). Increased reuse and recycling of water and increased use of saline water and oil-based fluids for drilling and hydraulic fracturing may help offset the higher water demand of important unconventional gas resources.

Oil

Water requirements for exploration, drilling, and primary production of conventional oil wells are similar to those for conventional natural gas wells. During primary production, reservoir pressures facilitate movement of oil up the well bore, and water use is minimal. With time, however, reservoir pressures decline; to enhance productivity, injection wells are drilled across the field to pump water into the formation to drive hydrocarbons to producing wells. This process, referred to as secondary production or water flooding, has higher water-use rates (fig. 5), up to about 8.6 liters of water per liter of oil (L-water/L-oil) (Wu and others, 2011), although produced or other non-freshwaters are often used in secondary production. With time, water flooding becomes less effective, as the oil remaining in the reservoir is typically trapped in small isolated pockets. A range of tertiary or enhanced oil recovery techniques can then be employed to extract a portion of the remaining product. Estimated rates of water consumption for enhanced recovery vary from 1.9 L-water/L-oil for forward combustion/air injection up to 13 L-water/L-oil for carbon dioxide (CO_2) injection (Gleick, 1994; Wu and others, 2011). Given current interest in carbon capture and storage, CO_2 injection is the fastest growing category of enhanced recovery in the United States (National Energy Technology Laboratory, 2010). As with secondary production, much of the water needs for enhanced recovery can be met by use of recycled, produced, or other non-freshwaters.

As with natural gas, development of unconventional shale and tight oil reservoirs typically requires more water than that required for primary production of conventional oil reservoirs (table 1). The higher water requirements are largely due to the water needed for hydraulic fracturing. Hydraulic fracturing of a well in units such as the Eagle Ford Shale in Texas can require upwards of 50 million L of water (Nicot and others, 2011).

Oil sands are bitumen-bearing, poorly consolidated sediments that constitute a large oil resource for North America. The largest continental source of oil sands is the Athabasca Tar Sands in Alberta, Canada. Oil sands are a relatively small energy source in the United States (U.S. Bureau of Land Management, 2012), but approximately 112 billion L of oil were produced from oil sands in Canada in 2012 (Alberta Government, 2013), accounting for more than 50 percent of that country's oil production. Data from the Province of Alberta indicate that water requirements for the development of oil sands are similar to those for the development of tight

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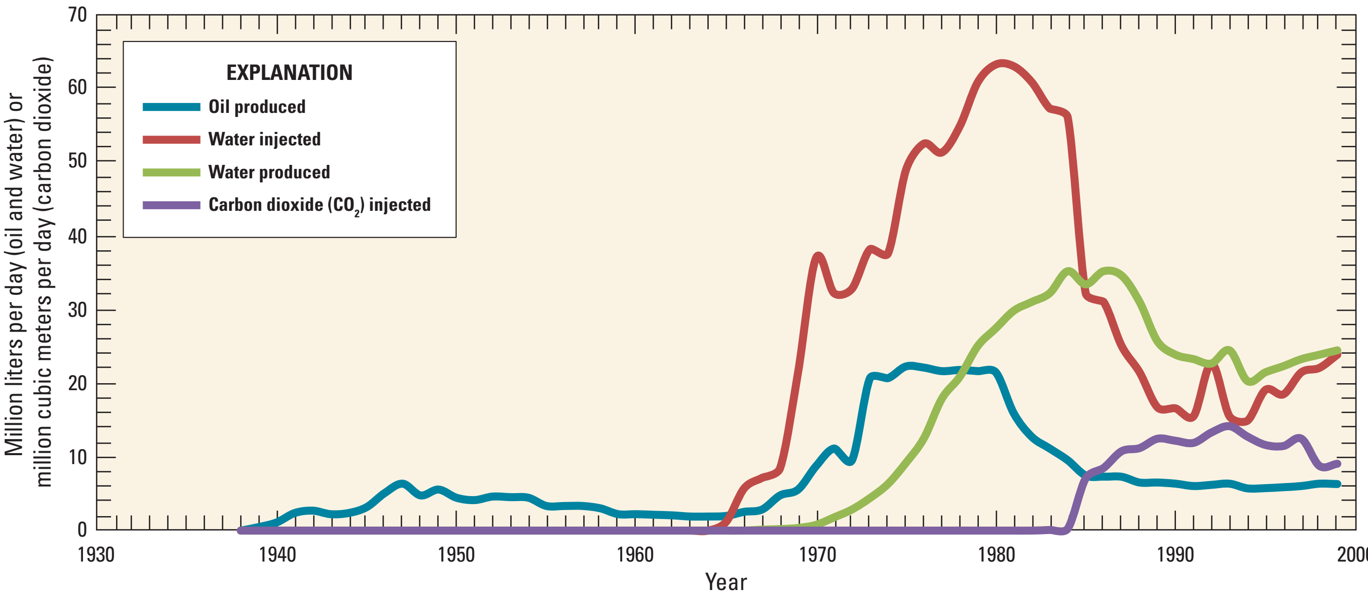

Figure 5. Oil and water production and water and CO_2 injection as part of primary, secondary, and tertiary production periods for the Denver Unit of the Wasson Field, west Texas, 1938–1988, with enhanced oil recovery (EOR) during tertiary production indicated. (From National Energy Technology Laboratory, 2010)

D The Marcellus Shale—A Vast Energy Resource with Important Challenges

The Marcellus Shale is a Middle Devonian siliciclastic black shale that extends along a large portion of the Appalachian Basin Province (fig. D–1) at depths of up to 2,000 m below land surface. It holds immense quantities of natural gas; the median estimated undiscovered, recoverable gas is about 2.38 trillion m^3 (Coleman and others, 2011), making the Marcellus one of the largest shale gas resources in the United States. The first Marcellus Shale gas well went into production in 2005, producing 0.16 million m^3 of gas in the first month (Carter and others, 2011). Since that time, oil and gas production from the Marcellus Shale has grown rapidly. In 2012, 2,246 permits were issued for unconventional oil and gas wells in Pennsylvania alone (Pennsylvania Department of Environmental Protection, 2012).

The rapid development of natural gas in the region comes with a number of tradeoffs and challenges. The energy boom has led to greater national energy security and lower energy prices for the consumer and has also generated numerous new jobs in a region hit hard by the recession of 2008. There are, however, a number of potentially adverse consequences associated with the energy development, including altered lifestyles, overloaded public infrastructure, and deterioration in quality of water, land, air, and ecosystem resources (Kappel and others, 2013). Land clearing for drilling pads, pipelines, compressor stations, and new roads can substantially alter landscapes, promoting increased soil erosion that can lead to contamination of streams and choking of ecosystems. Heavy traffic can damage existing roads and contribute to air pollution and traffic congestion. Hydraulic fracturing raises concerns among many people in regard to water supply and contamination (see Box C—Hydraulic Fracturing). Defective or improperly constructed retention ponds, pipelines, and wells can lead to unintended releases of hydrocarbons and produced waters and the contamination of surface water and groundwater.

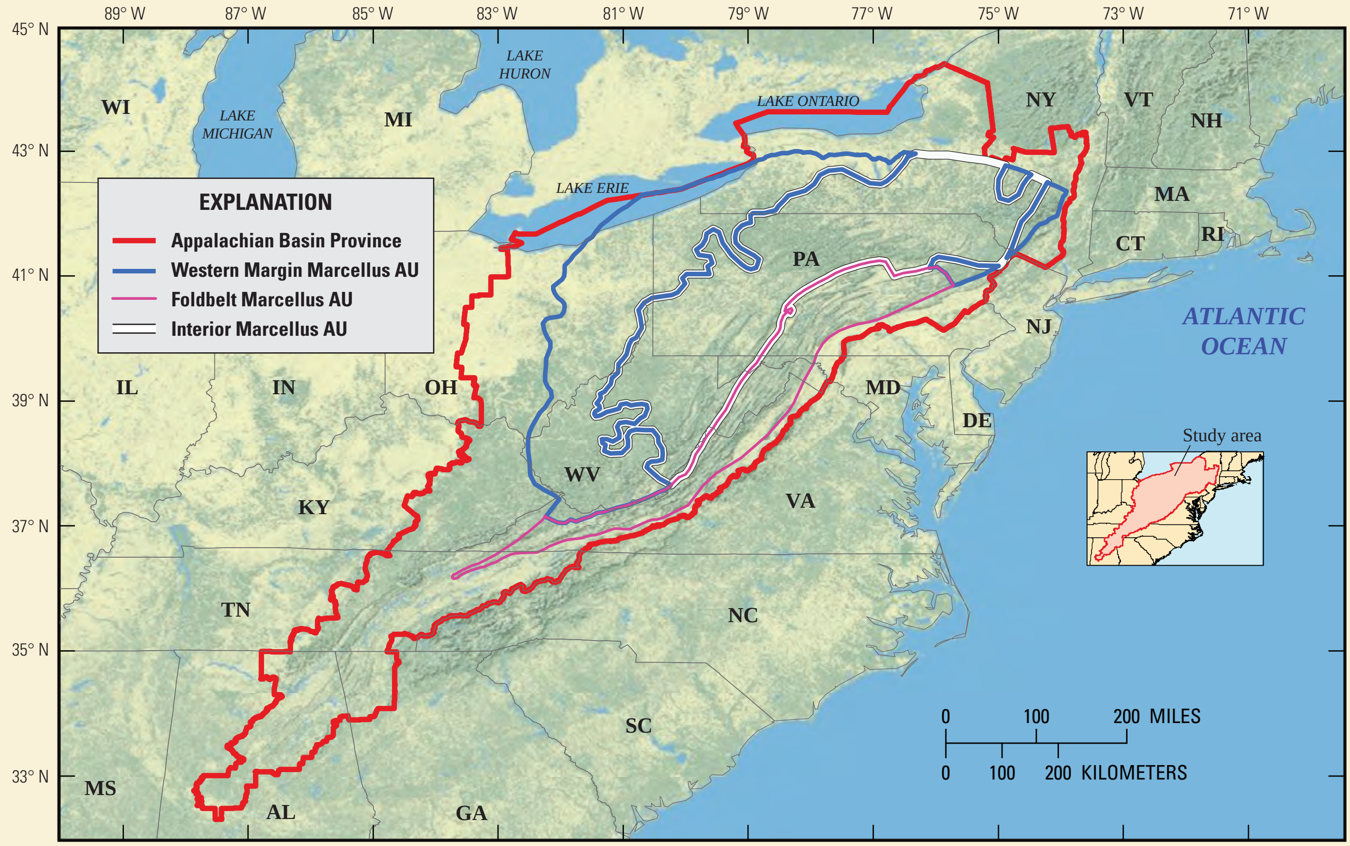

Figure D–1. Map showing the extent of the Appalachian Basin Province and the three assessment units (AUs) of the Marcellus Shale used in its resource assessment. (Coleman and others, 2011) oil wells (table 1). The water needed for oil sands development is extracted within a relatively small area; the effect of those large extractions on other local water users is as of yet unknown. Saline groundwater and recycled process waters can be used in place of freshwater in some oil-sand operations (Alberta Government, 2013).

Oil shale consists of kerogen-rich shale and fine-grained sedimentary rocks from which oil can be extracted by heating. There are no commercial oil-shale developments currently (2014) in operation in the United States, but oil shale is a potential energy source for the future. Oil shale can be mined and transported to a surface facility to be processed, or it can be processed in place. In-place production involves heating the shale in the ground to release the hydrocarbons and allow them to flow to collection systems (U.S. Bureau of Land Management, 2012). Preliminary estimates indicate that water consumption rates for the development of oil shale may not be substantially greater than those for secondary development or enhanced oil recovery of a traditional oil well (table 1). The Green River Formation, found throughout portions of Wyoming, Colorado, and Utah, is the largest oil-shale resource in the world, holding an estimated 424 trillion L of oil in place (Johnson and others, 2009; Johnson and others, 2010). It is located in areas of arid and semiarid climates where water resources are scarce; the rate at which oil can be produced from the formation might ultimately be determined by the availability of water.

Crude oil undergoes several chemical processes at refineries in order to create usable end products such as gasoline, diesel fuel, and jet fuel. Water is required in a number of these processes, primarily for cooling and condensing both steam and end products after chemical reactions. Water that is withdrawn for cooling, however, is not always consumed; refineries recycle and reuse much of their cooling water. The exact refinery processes vary with the form of the crude oil and end product, but estimated water requirements vary little. Refineries need ready access to large supplies of water. Estimated water consumption at refineries is about 1.4 L of water per L of end product (Wu and others, 2011). On a daily basis in 2013, U.S. refineries processed about 3 billion L of crude oil (U.S. Energy Information Administration, 2014b), and in so doing consumed about 4.2 billion L of water. If the largest refinery in the country, in Baytown, Texas, operated at its full capacity of 90 million L of oil per day, it would consume on the order of 125 million L of water daily, equivalent to about 13 percent of the average daily amount of wastewater treated in nearby Houston (City of Houston, 2013).

Water Quality

Infrastructure and Development Practices

Infrastructure and practices used in oil and gas production have the potential to produce unintended environmental consequences. Under natural conditions, subsurface reservoirs are isolated from each other by low-permeability geologic layers or seals, such as shales and mudstones, which prevent vertical migration or mixing of fluids contained in the reservoirs. These natural barriers are one reason why shallow groundwater can remain relatively fresh despite being underlain by saline brines and large hydrocarbon accumulations (fig. 2). Perforation of geologic seals by oil and gas wells provides potential pathways for fluids to move from one reservoir to another, but modern oil and gas wells are designed in such a way as to prevent this from happening. Typically, multiple casings are installed at each well to prevent unintended fluid movement between reservoirs (fig. 6). Cement grout is injected into portions of the annulus between the casings and between the outermost casing and the surrounding formation as a seal. Tests are conducted according to regulatory and best industry guidelines to ensure fidelity of the wellbore and integrity of the cement grout (Hetrick, 2011). Despite caution and testing, the integrity of the casing and grout can be inadequate or deteriorate with time, and the potential exists for pathways to develop along the wellbore that would permit migration of natural gas, oil, formation fluids, and injected fluids. Of particular concern is the migration of fluids in the annulus between the outermost casing and the adjacent formation (Mordick, 2011). Unintended or stray migration of natural gas along production wellbores has been a chronic problem for the oil and gas industry (Stein and others, 2003). Bexte and others (2008) showed that when very careful grouting procedures

Continued on page 19

The term salinity refers to the amount of salt in a given water sample; it is usually is expressed in terms of total dissolved solids (TDS). Water with a TDS concentration greater than 1,000 mg/L commonly is considered saline. This somewhat arbitrary upper limit of freshwater is based on the suitability of water for human consumption. Water with a TDS concentration greater than 1,000 mg/L is used in some areas, but water containing more than 3,000 mg/L is generally too salty to drink. The term "brackish" is sometimes used to describe water with TDS greater than 1,000 mg/L but less than 10,000 mg/L. Water with salinity greater than seawater (about 35,000 mg/L) is referred to as brine.

E A Tale of Two Basins—Water Surplus/Water Deficit

The Powder River Basin and the Williston Basin are adjacent structural basins within the Great Plains Physiographic Region (fig. E–1). Both basins have a semiarid climate, and both have been important sources for energy resources since at least the middle 1900s. The implementation of newer technologies for recovering fossil fuels has led to increased rates of development in both basins; however, different fuels and different practices between the basins have led to something of a conundrum—a large surplus of water in one basin and a substantial shortage of water in the other.

The Powder River Basin covers an area of about 61,000 km^2 in northern Wyoming and southern Montana. The basin is an important source of coal, oil, and natural gas. Coalbed natural gas development has expanded rapidly throughout the basin since the late 1990s; between 2000 and 2010, more than 59,000 well-drilling permits were approved in Wyoming (Wyoming Oil and Gas Conservation Commission, 2011). Natural gas is captured by withdrawing water from coalbeds; lowering the water pressure releases the gas.

About 85 billion L of water were produced annually in the Wyoming portion of the basin between 2002 and 2013 (fig. E–2). The produced waters are fresh to moderately saline (dissolved solids concentration in the range of 200–4,000 mg/L), but they have high proportions of sodium relative to calcium and magnesium, thus rendering the waters unsuitable for irrigation without treatment. A range of disposal options have been utilized, including storage in infiltration impoundments, treatment for irrigation or for release to streams, and reinjection into the subsurface (Bern and others, 2013a). The cost of these options and the possibility of adverse environmental consequences raise questions about the continued viability of coalbed natural gas development in the Powder River Basin.

The Williston Basin encompasses approximately 365,000 km^2 in eastern Montana, western South and North Dakota, and southern Saskatchewan. Oil was first discovered in the basin in the 1920s, and large-scale production began in the 1950s. A peak in oil production occurred in 1986, and production tapered off until the early 2000s (fig. E–3) when new techniques allowed oil reserves in the Bakken Formation to be tapped. Estimates of recoverable oil exceed 1 trillion L, making the Williston one of the largest oil-producing areas in North America.

Oil recovery from the Bakken Formation is economically feasible only because of recent improvements in directional drilling and hydraulic fracturing. A typical well in the Bakken Formation is drilled to a depth of about 3 km; the drill hole is then extended laterally within the formation for a distance of about 3 km. Hydraulic fracturing is used to increase permeability in the vicinity of the drill hole so that oil will flow more freely to the well. The fracturing is done incrementally over the length of the horizontal section of the well, requiring an average of about 10 million L of water for each well (Scanlon and others, 2014).

The number of wells drilled in the North Dakota portion of the Bakken Formation is projected to be about 2,000 per year (Lymn, 2014). This equates to approximately 20–40 billion L of water per year, much less than the annual excess produced water in the Wyoming portion of the Powder River Basin. Water is a limited resource in western North Dakota, and most available water was long ago allocated for existing agricultural, industrial, and municipal interests. Water for well development must be obtained from entities that currently own water rights. As more and more wells are drilled, the demand (and the price) for water will only increase.

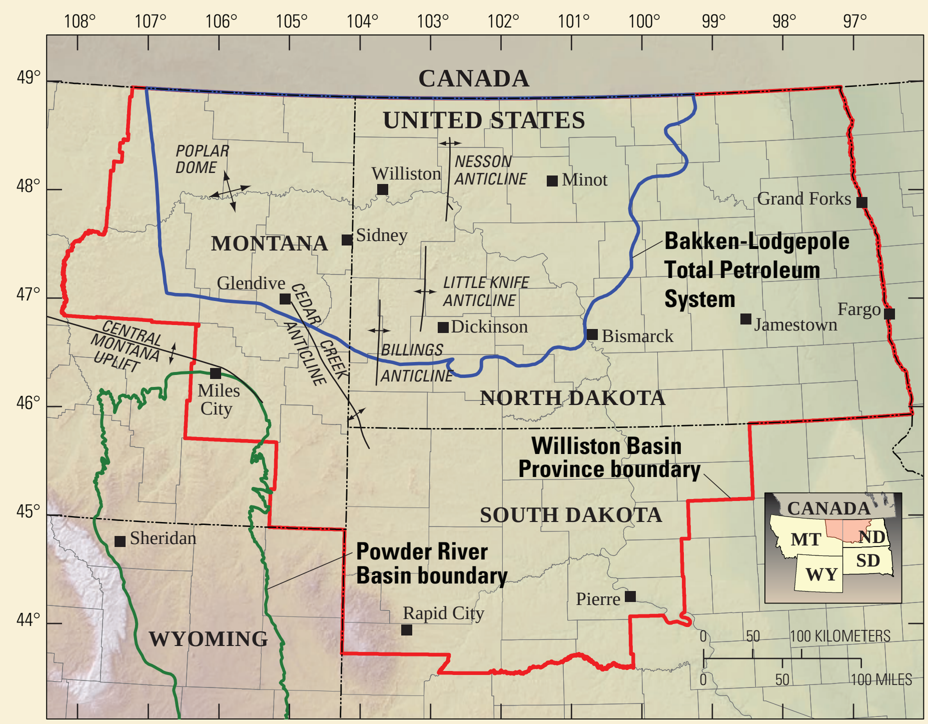

Figure E–1. Map showing Powder River Basin and Williston Basin.

So why not use Wyoming's produced water for well development in Montana and North Dakota? The answer is mainly one of economics. Water is expensive to transport unless natural stream channels can be used. The high sodium concentration of the produced water makes it inappropriate for direct discharge to streams because of concerns related to stream ecology and downstream irrigators. Alternative transport options such as truck and rail lines or the construction of a dedicated water pipeline are currently (2014) nonviable.

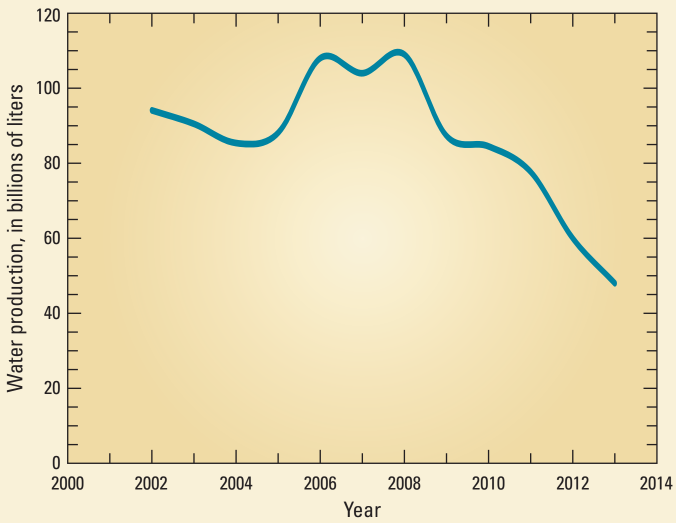

Figure E–2. Water production for coalbed natural gas in the Powder River Basin, Wyoming, 2002–2013. (Wyoming Oil and Gas Conservation Commission, 2014)

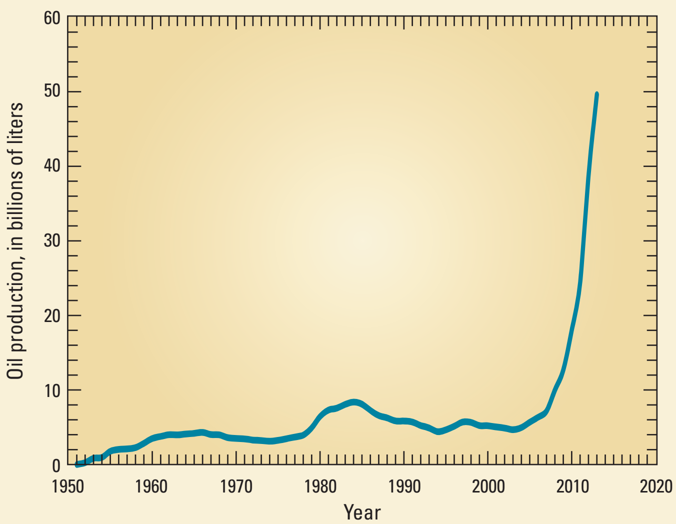

Figure E–3. Annual oil production in North Dakota, primarily from the Williston Basin, 1950–2013. (Data from North Dakota Oil and Gas Division, 2014)

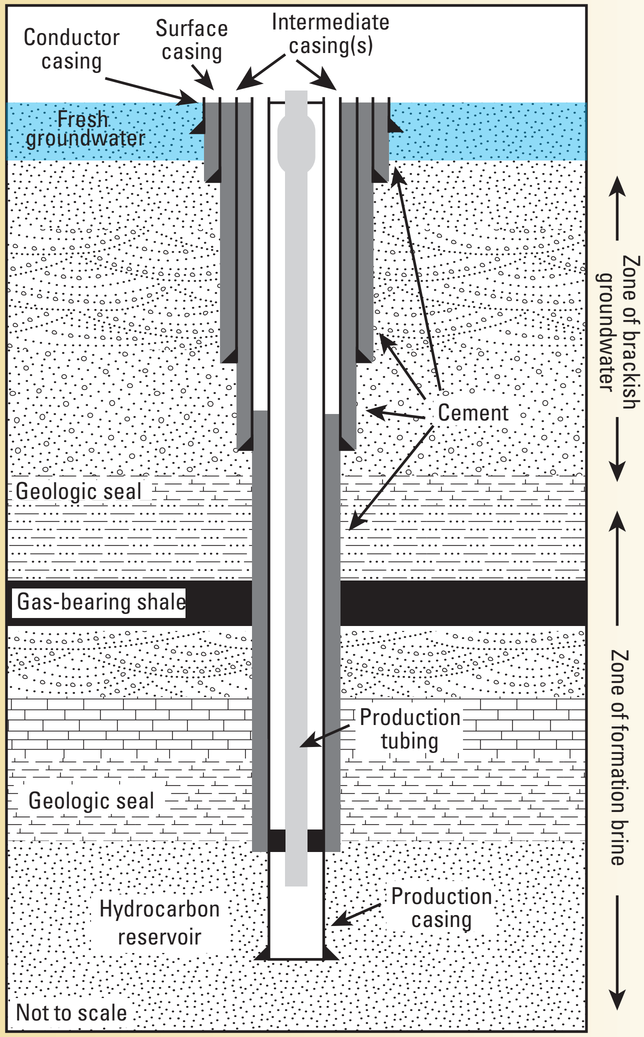

Figure 6. A modern vertical oil or gas well (based on Teodoriu and Falcone, 2008). The cement seal may not extend over the entire vertical extent of a well. Some States require isolation of only freshwater and gas-producing zones.

are used, natural gas movement along casings occurred in about 1 percent of newly installed horizontal wells in Alberta, Canada.

Oil and gas wells are abandoned when the resource has been depleted or it is not economically practical to continue resource extraction. Abandoned wells, if not properly sealed, can serve as conduits for the contamination of freshwater aquifers. Extended lengths of oil and gas wells can be uncased and thus open to many different geologic units and aquifers. If one of those geologic units becomes a target for nearby operations, such as hydraulic fracturing or wastewater injection, then the injected fluids could potentially be transported through the abandoned well to a freshwater aquifer. State laws require that oil

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F Gasoline Additives—Clean Air vs Clean Water? The MTBE Story

MTBE (methyl tertiary butyl ether) was first introduced into gasoline in 1979 as an octane enhancer. It replaced the tetraethyl lead that was being phased-out because of concerns about lead in the environment (U.S. Environmental Protection Agency, 1999). Use of MTBE expanded with passage of the Clean Air Act amendments of 1990, which required that areas with severe ozone-smog problems use reformulated gasoline that includes an "oxygenate." Oxygenates are compounds that contain oxygen and when added to gasoline improve combustion and reduce harmful motor vehicle emissions.

By the late 1990s, MTBE made up 3 to 5 percent of the national gasoline supply. From 1993 to 1998, it was the second most produced organic chemical in the United States (Moran and others, 2004). Also at this time, MTBE started showing up in groundwater and in some reservoirs and rivers used as public water supplies (U.S. Environmental Protection Agency, 1999). Apparently, in trying to solve an air pollution problem, a water contamination problem was created.

Its physical properties make MTBE a prominent groundwater contaminant. It dissolves easily in water and does not tend to become affixed to soil and aquifer material, thus moving as quickly as water through the subsurface. It is also slow to biodegrade and can persist longer in groundwater than many other organic compounds, including other components of gasoline, such as benzene and toluene (Zogorski and others, 2006). There are numerous potential sources of MTBE in groundwater, including leaking storage tanks, leaks and accidents during transport, homeowner gasoline spills, stormwater runoff, and even precipitation scavenging MTBE in the air.

The U.S. Environmental Protection Agency (EPA) considers MTBE a possible carcinogen, although the human health effects have not been clearly established (U.S. Environmental Protection Agency, 1999). What really brought MTBE to the forefront was that even very low concentrations of MTBE make water taste and smell "foul and nasty," like turpentine. In 1997, EPA issued a drinking water advisory indicating that MTBE concentrations in drinking water below the range of 20–40 parts per billion (ppb) will likely avert unpleasant taste and odor effects, although some people can detect the chemical at concentrations as low as 1 ppb (U.S. Environmental Protection Agency, 1999). The lower threshold of 20 ppb also was considered to be protective of human health while further studies of the risks were underway.

The first major MTBE groundwater contamination incident occurred in Santa Monica, California. In 1996, the city discovered that two of its drinking water well fields were contaminated with high levels of MTBE (U.S. Water News Online, 1996). The two well fields, representing half of the city's drinking water supply, were shut down and the city was forced to purchase replacement water until the groundwater supply was restored with a treatment system in 2010. (Shorney-Darby and others, 2011).

Low concentrations of MTBE have been detected in groundwater nationwide, particularly in the highly populated New England and Mid-Atlantic States where MTBE

Smog attributed to motor vehicle emissions was common in many metropolitan areas of the United States prior to the implementation of Federal and State gasoline programs.

use was high (fig. F–1). Despite its relatively short history of use, MTBE was the second most frequently detected volatile organic compound in a national survey of drinking-water wells (after chloroform) (Zogorski and others, 2006). It was detected in about 5 to 10 percent of community drinking water supplies in high oxygenate use areas, but concentrations were generally less than 1 ppb (U.S. Environmental Protection Agency, 1999). Although the MTBE concentrations were low, the relatively high rate of detection illustrates how susceptible some aquifers are to low-level contamination and how quickly widespread groundwater contamination can occur from a widely used chemical.

In 1999, a Blue Ribbon Panel on oxygenates in gasoline created by the EPA recommended that the requirement for an oxygenate in gasoline in large cities be dropped and that overall use of MTBE in gasoline be "reduced substantially" (U.S. Environmental Protection Agency, 1999). That same year, California ordered oil companies to phase out MTBE in gasoline by 2002 (later extended to 2003). By 2004, 19 States had enacted legislation to completely or partially ban MTBE use in gasoline (U.S. Environmental Protection Agency, 2004). The Energy Policy Act of 2005 eliminated the oxygen requirement in gasoline nationwide and accelerated the use of ethanol as an alternative. The use of MTBE and the subsequent rise in the use of ethanol indicate how air pollution, water pollution, and energy can be tightly linked with complex and sometimes unanticipated tradeoffs.

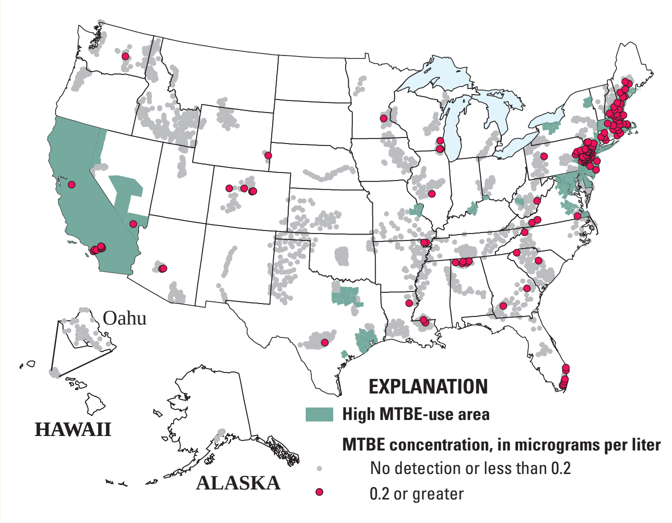


Figure F–1. Locations where methyl tertiary butyl ether (MTBE) was detected in groundwater in the United States, 1985–2001. Most detections of MTBE in groundwater were in the highly populated New England and Mid-Atlantic States where MTBE use was high. (From Zogorski and others, 2006)

and gas wells be sealed after production ceases. Sealing typically involves setting plugs and (or) cementing portions of the well, particularly within and above the producing formation and within and below shallow freshwater aquifers (National Petroleum Council, 2011). However, poor industry guidelines, less-than-ideal materials, and weak or absent laws regarding well abandonment prior to 1950 have left many areas of historic oil and gas production with an abundance of improperly sealed wells (National Petroleum Council, 2011). In some cases, well casings were completely removed for reuse, leaving the original wellbore open (Hammack and others, 2006). Improperly plugged and abandoned wells present an avoidable and potentially concerning avenue for the migration of brines, hydrocarbons, and surface contaminants to shallow aquifers (Shedlock, 1980; Osborn and others, 2011). In efforts to protect drinking water supplies, many States and energy companies have taken steps to locate and properly seal abandoned oil and gas wells, although this is a massive undertaking (Ground Water Protection Council, 2011). West Virginia alone has more than 12,000 known abandoned oil and gas wells (West Virginia Department of Environmental Protection, 2010).

Transportation, storage, and processing of oil, natural gas, and produced waters can also affect water quality. It is estimated that more than 4 million kilometers (km) of pipelines for hazardous chemicals (mostly oil and gas) exist within the United States (U.S. Pipeline and Hazardous Materials Safety Administration, 2014b). In addition, there are more than 500,000 oil and gasoline storage tanks (U.S. Environmental Protection Agency, 2012b). Any of these pipes and tanks has the potential to develop leaks, and any leak has the potential to contaminate both surface water and groundwater. For the period 1994–2013, the U.S. Pipeline and Hazardous Materials Safety Administration (2014b) reported a total of 5,622 significant pipeline incidents; the resulting property damage was in excess of 6 billion dollars. For 2011, more than 6,000 leaks from underground storage tanks were reported (U.S. Environmental Protection Agency, 2012b). Leaks can occur as the result of faulty materials, improper installation, and natural disasters such as hurricanes, earthquakes, and tsunamis, which can cause severe damage to energy infrastructure. As an example, more than 26 million L of oil reportedly leaked from pipelines and storage tanks around New Orleans in 2005 as a result of Hurricane Katrina (Llanos, 2005).

Oil refineries are large industrial complexes that process millions of liters of crude oil daily. Operations conducted at these complexes release a variety of pollutants to the atmosphere—including carbon dioxide, volatile organic compounds, benzene, sulfur dioxide, and nitrous oxide—that can contaminate water (U.S. Environmental Protection Agency, variously dated). Refineries can contain hundreds of storage tanks and reaction vessels as well as many kilometers of pipelines. The extensive infrastructure and the high volume of material processing raise the potential for leaks that could eventually contaminate water. A leak at a refinery in Commerce City, Colo., which might have gone undetected for years, resulted in benzene contamination of shallow groundwater and the South Platte River (Finley, 2012). As mentioned above, catastrophic events such as Hurricane Katrina can also lead to contaminant releases in refineries.

Produced Water

Natural gas and oil extracted from geologic reservoirs are usually intermixed with large volumes of produced water. Produced waters are a mixture of water naturally present in the reservoir, liquids used in the drilling and development process, and possibly hydrocarbon compounds associated with natural gas or oil. The chemistry of these waters vary, but they can be many times more saline than seawater and can include inorganic salts, dispersed oil, dissolved organic compounds, radionuclides, bacteria, and solids (Veil and others, 2004).

Approximately 3.3 trillion L of produced water were generated in the United States in 2007 from about 1 million production wells (Clark and Veil, 2009). Currently, there is no national repository for quantitative information on produced water, but many states maintain databases containing the amounts of produced waters that are generated and the disposition or use of those waters. Clark and Veil (2009) compiled a table of produced water quantity and disposition on a state-by-state basis for 2007. Approximately 98 percent of produced water generated onshore in the United States in 2007 was injected into the subsurface (Clark and Veil, 2009); approximately 59 percent was injected into oil-producing formations as a part of secondary recovery operations to force oil toward producing wells, and almost 40 percent was injected solely for the purpose of disposing of the water. Only a small portion of produced waters in the United States presently is used for beneficial purposes, but recent research has led to increased efforts to identify beneficial uses of these fluids (see Box G—Produced Waters—An Underused Resource?). Transport and treatment of large volumes of produced water continues to be an important management issue in the United States.

Production rates for oil, natural gas, and water from individual wells vary depending on the specific resource being extracted, the type of reservoir, and the elapsed production time (fig. 7). Conventional oil and natural gas wells typically exhibit fairly rapid drop-off in hydrocarbon and water production. Shale-gas wells produce the majority of their water in the first few days of production, whereas oil wells tend to exhibit higher water-to-oil ratios as they mature (Clark and Veil, 2009). Veil and others (2004) noted, for instance, that the average water-to-oil ratio for operational wells in the United States increased from 7.5 to 9.5 L-water/L-oil between surveys conducted in 1996 and 2002; they attributed the increase in water production from increasingly mature fields. Obviously water flooding, as a form of secondary oil recovery, has potential to greatly increase the volume of water produced from a reservoir. In very late stage production, the water-to-oil ratio can be as high as 10–20 L-water/L-oil (Veil and others, 2004). In contrast, large volumes of water must be pumped from the coalbed natural gas reservoirs before gas can be extracted (fig. 7). Managing both water and hydrocarbon production can be complicated, especially across entire plays, where wells of differing maturity are operating at the same time.

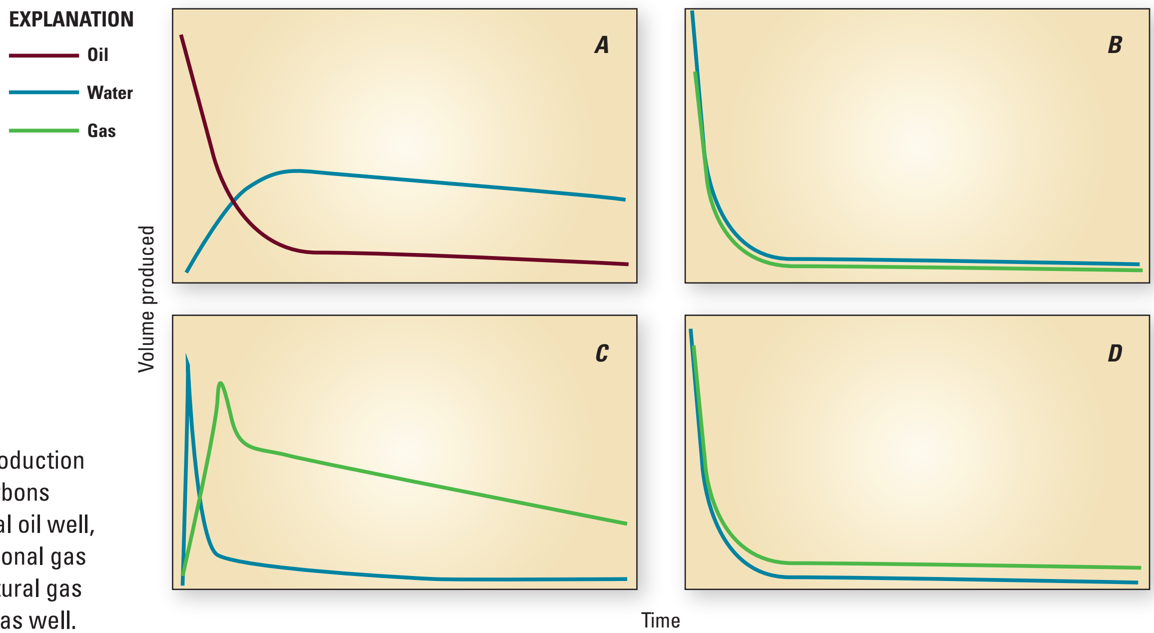


Figure 7. Relative production of water and hydrocarbons from (*A*) a conventional oil well, (*B*) a shallow conventional gas well, (*C*) a coalbed natural gas well, and (*D*) a shale gas well.

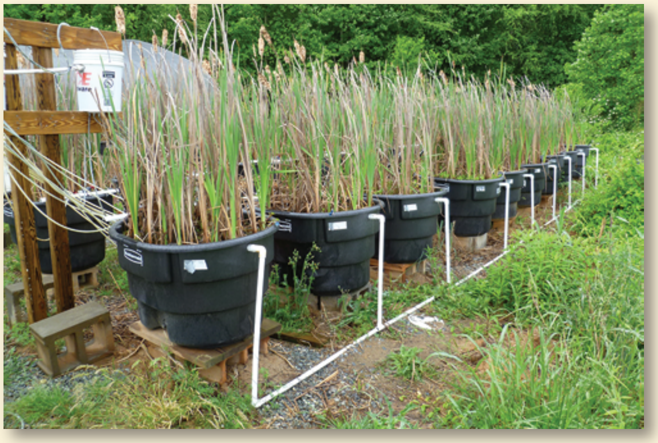
G Produced Waters—An Underused Resource?

Produced waters that are not injected back into the subsurface can be recycled and put to a variety of beneficial uses. Recycling of produced waters has two main benefits—reducing freshwater consumption and decreasing the volume of produced fluids to be disposed. Coalbed natural gas produced waters with relatively low salinity (less than 3,000 mg/L dissolved solids) in the Powder River Basin of Wyoming and Montana are being used for livestock and, after treatment, for irrigation of forage crops (Bern and others, 2013a,b). In cold regions, produced waters with high salinity (about 100,000 mg/L dissolved solids) are sometimes applied to roads to inhibit ice formation. Other industrial uses include dust control, equipment washing, input for steam conversion, and fire control (Veil and others, 2004).

In addition to reuse of produced waters, constituents within the waters might have economic value. Brines historically have been an important commodity in many parts of the United States. A variety of salts, calcium, magnesium, iron, bromide, and iodide can be produced for profit from brines after heating them in furnaces or evaporators (Price and others, 1937). Secondary chemicals such as hydrochloric acid can be produced from the bitterns of these fluids. More recently strategic commodities, such as lithium, an important element in the production of batteries, are being extracted from some produced waters (Engle and others, 2014).

Treatment of produced water might be required prior to use, discharge, or reinjection. Treatment technologies range from complete desalinization or distillation systems, which produces potable water, to passive constructed wetland systems that remove potential pollutants, such as oil and grease, salts, dissolved organics, suspended solids, metals, and radionuclides (Engle and others, 2014). Energy producers must weigh the economic tradeoffs involved in treatment, injection, and possible beneficial uses.

Alfalfa field irrigated with pH-adjusted water from nearby coalbed natural gas wells, Johnson County, Wyoming.



Pilot-scale constructed wetland water-treatment system designed to break down and remove potential environmental contaminants in produced waters through biogeochemical processes.

Coal

Coal continues to be the primary fuel for generation of electricity in the United States. In 2013, approximately 890 million metric tons of coal were extracted in the United States, 91 percent of which was used to generate electricity (U.S. Energy Information Administration, 2014b). Water is associated with all stages of energy production from coal—extraction, transportation, processing, combustion, and disposal of waste products—bringing up issues of water supply and water quality. The importance of these issues depends on many factors, including mining method, climate, and the chemistry of the coal and adjacent rocks.

Coal, which is found in many regions in the United States (fig. 8), is classified on the basis of rank, a measure of progressive alteration from lignite (low rank) to anthracite (high rank). Higher rank coals usually have greater energy contents. Coals in the eastern part of the United States generally have a higher rank than coals in the west. Western region coals, however, have lower sulfur contents per unit energy content and, hence, produce less sulfur-dioxide air pollution upon combustion. As a result, production from coal mines west of the Mississippi River increased substantially from 1970 to 2011 (40.7 million to 579 million metric tons), whereas production from mines east of the Mississippi River remained fairly steady at about 450 million metric tons per year for the same time period (U.S. Energy Information Administration, 2012a).

Coal is extracted from both surface and underground mines. In surface mining, the rocks overlying the coal seam (the overburden) are moved to a temporary storage area, and the coal is extracted. The overburden might then be replaced, the land surface is recontoured to its approximate original position, and vegetation is replanted. Mountaintop removal mining is a large-scale form of surface mining that is commonly used in portions of the central Appalachian Basin, including Virginia, West Virginia, Tennessee, and Kentucky (U.S. Environmental Protection Agency, 2014e). In this process, entire mountaintops and ridges are removed to expose the underlying coal. As much as 300 meters (m) of overburden is removed, and much of it is deposited into adjoining valleys. Mountaintop removal mining can substantially alter the hydrology of a watershed—ditches are usually constructed to funnel runoff and drainage from the mine to a sedimentation pond and eventually to a flowing stream, natural stream channels and springs might be buried beneath overburden, and groundwater flow patterns can be disrupted. Post-mining reclamation efforts include recontouring of the land surface, but landscapes, hydrology, and ecosystems remain permanently altered (U.S. Environmental Protection Agency, 2014e).

Underground mines leave the overburden in place; the coal is extracted and transported to the land surface through a series of tunnels. Reclamation of underground mines usually includes returning the land surface to near pre-mining conditions and installing safeguards to minimize water drainage and subsidence from the network of tunnels (Gleick, 1994). Annual production from underground mines has remained fairly stable since 1950 at about 300 million metric tons (U.S. Energy Information Administration, 2012a), whereas production from surface mines increased steadily from 1950 to 2011 (126 million to 679 million metric tons).

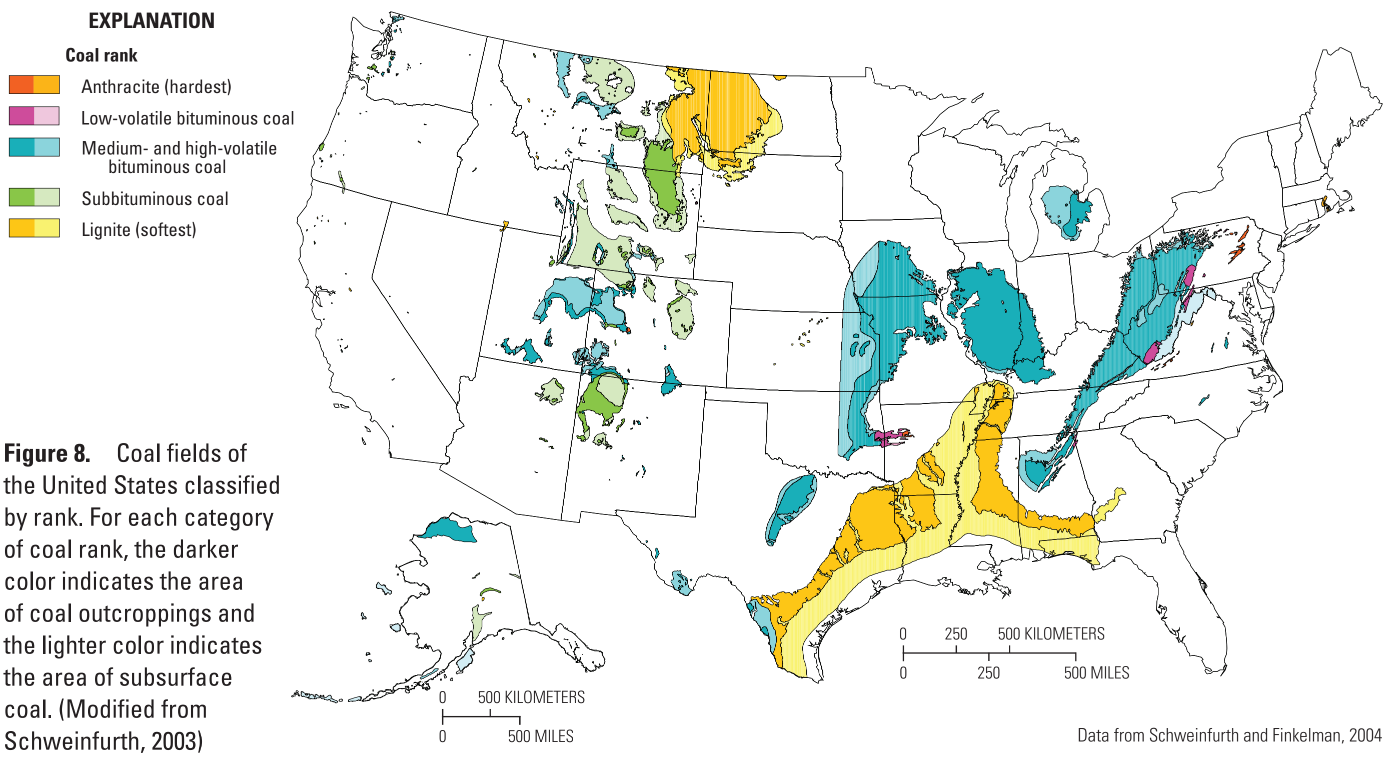


Figure 8. Coal fields of the United States classified by rank. For each category of coal rank, the darker color indicates the area of coal outcroppings and the lighter color indicates the area of subsurface coal. (Modified from Schweinfurth, 2003)

Mountaintop coal removal mine in West Virginia during the reclamation process. The hills in the background are likely similar to the original topography and vegetation at the mine site.

Water Use

Water is involved in all aspects of mining and processing of coal. For mining, the relevant issues are associated with mine dewatering, cooling of drilling equipment, cleaning of coal, dust suppression, waste disposal, reclamation, revegetation, and possibly transportation. Coal can be processed into gaseous or liquid fuels, operations which also require water.

Groundwater extracted for mine dewatering may or may not be viewed as consumed water. The extracted water can be used to satisfy many of the water needs of the mine, and excess water is usually discharged to a stream or other surface-water body, keeping it in the hydrosphere. Mine dewatering, however, does affect natural patterns of groundwater flow; the diversion of groundwater to a mine may also affect nearby stream flows and associated ecosystems by reducing natural rates of groundwater discharge to land surface.

Rates of water withdrawal and consumption by coal mines are not routinely measured in the United States, and relatively few studies have attempted to estimate these rates. Lovelace (2009) suggests a water withdrawal rate of 209–246 L per metric ton of coal, equivalent to a range of 186–219 billion L of water withdrawn for all of the coal produced in the United States in 2013, or roughly 3 percent of all water withdrawn for mining in 2010 (Maupin and others, 2014). Estimates of coal mine–related water consumption rates are provided in Gleick (1994), Pate and others (2007), Nicot and others (2011), and Meldrum and others (2013). Results of these studies suggest a wide range in water consumption rates for all phases of mining operations—between 75 and 500 L of water per metric ton of coal. The variability in these estimates is related to characteristics of the coal, mining processes, and methods used to generate the estimates. In general, the mining operation that consumes the most water is the irrigation of vegetation planted during reclamation—Grubert and Kitasei (2010) suggest 0.22 m of water per unit land surface area per year for a period of 10 years.

Mine-related water storage can also affect human health and safety. On February 26, 1972, a dam constructed with coal-mine waste on a tributary to Buffalo Creek in southwestern West Virginia collapsed, sending 500,000 m^3 of water and mine waste down to the valley floor. The accident resulted in the loss of 125 lives and more than 500 homes in the town of Saunders (Davies and others, 1972).

Coal gasification is the chemical process of turning coal into natural gas that has been in use for more than 100 years. In the late 1800s, coal gasification was used to provide gas for home lights before the widespread availability of electricity. The Great Plains Synfuels Plant near Beulah, N. Dak., is currently the only commercial-scale coal gasification plant in the United States. On a daily basis, approximately 4.1 million m^3 of synthetic natural gas is extracted from about 16,300 metric tons of lignite coal (Dakota Gasification Company, 2012). Water consumption rates for coal gasification, estimated to be in the range of 1.5–3.6 L/m^3 of gas (Gleick, 1994), are comparable to those for production of shale gas (table 1).

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A 439-km-long pipeline was used to transport coal from the Black Mesa mine in northern Arizona to the Mojave power plant in Nevada. It was the longest slurry pipeline in the world. Over the course of its operational life, from 1969 to 2005, approximately 5.6 billion L of water were used annually to transport about 4.5 million metric tons of coal. The pipeline was controversial because the water was obtained from the Navajo aquifer. That aquifer is the major source of water for municipal and industrial uses for an area of about 14,000 km^2 that has an arid to semiarid climate (Macy and others, 2012).

H Subsurface Fluid Injection—Risks of Groundwater Contamination and Earthquakes

Subsurface fluid injection refers to the process whereby fluids (most commonly water but also possibly wastes and carbon dioxide) are transferred from land surface to some depth in the subsurface through an injection well. The process has been in use in the United States for more than 100 years (Hickey and Vecchioli, 1986). Injection is used for a variety of purposes, such as the disposal of wastewater from municipal and individual (septic tanks) sources, aquifer replenishment, storm water disposal or storage, combatting salt water intrusion, and a number of energy-related purposes. Table H–1 and figure H–1 describe the different classes of injection wells used in the United States.

Subsurface injection was first used for disposal of produced waters from oil wells in the 1930s. Injection is still used for this purpose, but over the decades the number of energy-related applications of injection have expanded. Water is injected for secondary oil recovery, and CO_2 commonly is injected for enhanced oil recovery; in these operations, the injected fluids are used to force residual oil to pumping wells. Solution mining for uranium relies on the injection of water and chemicals to extract the metal. Geothermal power plant managers use fluid injection to maintain pressures in geothermal reservoirs. Deep injection of CO_2 is a key component of planned carbon capture and geologic sequestration programs.

Subsurface injection occurs throughout the United States. In the case of extraction of oil or minerals, the injection takes place in the location of the targeted asset. In the case of injection of produced water or wastewater, economics dictate that the injection point be located in proximity to the where the injectate is produced in order to minimize transportation costs; however, locating a suitable receiving formation can be problematic. Injection in oil fields can occur in production wells that have gone dry or in wells installed specifically for injection. Injection of CO_2 for future carbon sequestration will likely occur in the vicinity of a CO_2 source and will require installation of wells specifically for injection (see Box K—Carbon Capture and Sequestration).

Host formations that receive injected fluids generally lie at depths of several hundred meters or more, much deeper than most aquifers that are used for drinking water. Primary storage space in these formations is created by displacing native, saline water. Smaller amounts of storage are created through the enhancement of total pore space in the native rock and by compression of the injected fluids. Potential adverse effects of subsurface injection include groundwater contamination and induced seismic activity. Groundwater can become contaminated if the injected fluid or displaced native water seeps into freshwater aquifers. Contamination can occur if the injection formation is not isolated from these aquifers; if the injection pressure is too high, causing inadvertent fracturing to occur; or if there are other avenues for water movement, such as abandoned wells or improperly completed wells.

Induced seismicity refers to seismic activity (earthquakes) propagated by human actions. A number of activities, including the impoundment of reservoirs above dams, underground nuclear testing, and mining, are known to induce seismic

Table H–1. Class, use, and number of wells in the U.S. Environmental Protection Agency Underground Injection Control Program in the United States in 2011.

[From U.S. Environmental Protection Agency (2012c). USDW, underground source of drinking water (aquifer with concentrations of total dissolved solids less than 10,000 milligrams per liter)]

Class	Use	2011 Inventory
I	Inject hazardous wastes, industrial nonhazardous liquids, or municipal wastewater beneath the lowermost USDW.	680 wells.
II	Inject (1) brines and other fluids associated with oil and gas production, and (2) hydrocarbons for storage.	172, 068 wells.
III	Inject fluids associated with solution mining of minerals beneath the lowermost USDW.	22,131 wells.
IV	Inject hazardous or radioactive wastes into or above USDWs. These wells are banned unless authorized under a Federal or State groundwater remediation project.	33 sites.
V	All injection wells not included in Classes I–IV. In general, Class V wells inject nonhazardous fluids into or above USDWs and are typically shallow, onsite disposal systems. However, there are some deep Class V wells that inject below USDWs.	400,000 to 650,000 wells. Note: an inventory range is presented because a complete inventory is not available.
VI	Inject carbon dioxide (CO_2) for long-term storage, also known as geologic sequestration of CO_2.	6–10 commercial wells expected to come online by 2016.

activity. The injection or withdrawal of fluids to or from a subsurface hydrocarbon or water reservoir can also trigger seismic activity; in most cases this is caused by a change in pore fluid pressure or stress in subsurface rocks near faults that have specific properties (National Research Council, 2012). The National Research Council examined the occurrence of seismic activity in the United States related to geothermal energy development, conventional oil and gas development, hydraulic fracturing of shale gas wells, and carbon capture and sequestration (National Research Council, 2012). They found that seismic events have been produced by these activities in the United States but that the number of events large enough to be felt was quite low relative to the number of injection and withdrawal wells in operation (table H–2). Most events occurred as a result of an imbalance in fluid pressures within a reservoir; balancing fluid pressures by a combination of injection and withdrawal appears to reduce the likelihood of seismic events. Only one seismic activity resulting from hydraulic fracturing of a shale gas well has been reported, and that incident has not been confirmed (National Research Council, 2012). In regard to carbon capture and sequestration, it is difficult to assess the likelihood of induced seismic activity arising from CO_2 injection because there were no commercial-scale operations in the United States as of 2013; however, injection of CO_2 for sequestration could pose a greater risk of inducing seismic activity than other energy technologies because of the large volumes of CO_2 that are involved (National Research Council, 2012).

In order to promote successful subsurface fluid injection, Hickey and Vecchioli (1986) suggested that the injection site and surrounding area satisfy a number of hydrogeologic criteria, including (1) that the injection zone should be regionally extensive, not be penetrated by improperly abandoned wells, and be overlain and underlain by confining beds that will retard movement of injected fluids; (2) that the injected fluid be chemically compatible with the native rock and groundwater so as to avoid reactions that could plug the injection zone or produce toxic substances; and (3) that mineral or hydrocarbon resources be absent from the injection zone to preclude the possibility of future development.

Table H–2. Summary information on reported “felt” seismic events that could be attributed to energy-related activities.

[From National Research Council (2012). ~, aproximately; na, not applicable]

Technology	Number of projects	Number of “felt” induced events	Maximum magnitude of induced events
Vapor-dominated geothermal systems	1	300–400/year since 2005	4.6
Liquid dominated geothermal systems	23	10–40/year	4.1
Enhanced geothermal systems	~8 pilot studies	2–10/year	2.6
Oil field water flooding	~108,000 wells	One or more events at 18 sites	4.9
Enhanced oil recovery (EOR)	~13,000	0	na
Hydraulic fracturing—shale gas wells	~35,000	1	2.8
Hydrocarbon withdrawal	~6,000 fields	20 sites	6.5
Wastewater injection	~30,000	8	4.8

Figure H–1. Class I, II, and III wells, left to right, as defined by the U.S. Environmental Protection Agency Underground Injection Control Program. (From U.S. Environmental Protection Agency, 2012c)

Former site of the small town of Saunders, West Virginia, in the aftermath of the Buffalo Creek flood of February 26, 1972.

Coal liquefaction is a two-step process for turning coal into liquid fuels, such as gasoline, diesel, and kerosene, primarily for use in motor vehicles (National Energy Technology Laboratory, 2006). The first step consists of coal gasification. The second step converts the gas to liquid form by the addition of water and carbon dioxide. Coal liquefaction technology is well known, and the fuel that is generated can serve as a substitute for fuels derived from crude oil. Some countries with limited crude oil resources, such as South Africa, rely on coal to produce a large percentage of their transportation fuels (World Coal Association, 2014). Currently (2014), no domestic commercial coal liquefaction plants are in operation in the United States. Water consumption rates for production of fuel by coal liquefaction have been estimated at 5–7.3 L of water per liter of fuel (National Energy Technology Laboratory, 2006).

Water Quality

Water-quality concerns are often as important as those of water supply in regard to coal mining. Nationally, acid mine drainage is perhaps the most significant water-quality issue associated with coal extraction. Coal and rocks adjacent to coalbeds often contain sulfide minerals such as pyrite. When these rocks are exposed to air and water, oxidation reactions release sulfur and allow the formation of sulfuric acid. The resulting decreased pH levels in groundwater and surface water lead to increased concentrations of heavy metals, which may in turn render the waters toxic to fish and other aquatic life (Nordstrom and Alpers, 1999).

Acid mine drainage (AMD) can occur as a result of direct discharge of water used in coal-mining operations, such as for coal washing and dust suppression. It can also be generated when precipitation infiltrates coal and rock-waste piles at surface mines or when spoil retention dams fail. If underground mine shafts or surface waste piles are not properly sealed, AMD can occur for decades after a mine has been closed. Coal mines may be the largest source of AMD in the United States, but other mines, such as for gold, copper, and uranium, also produce AMD. A quantitative assessment of water contamination from AMD has not been conducted at the national level, but regional and local patterns are evident. A greater abundance of water and a higher sulfur content of coal make the eastern half of the United States more susceptible to AMD than the western half of the country. For example, AMD has affected approximately 2,100 km of streams in Ohio (Ohio Department of Natural Resources, 2014) and more than 4,300 km of streams in West Virginia (Corio, 2008).

Interestingly, mountaintop removal mining has been shown to reduce acid-mine drainage; water from these mines can be neutralized by minerals in the valley fill (Griffith and others, 2012). Constructed sedimentation ponds also facilitate water treatment to raise pH and reduce concentrations of metals. Nevertheless, mountaintop removal mining alters natural ecosystems, and streams draining valley fills tend to have higher concentrations of dissolved solids relative to unaffected streams (Lindberg and others, 2011; Griffith and others, 2012).

Uranium

Fuel for nuclear power plants comes from traditional surface and underground uranium mining and, more recently, from in-place extraction or leach mining. Production of nuclear fuel rods requires several levels of uranium processing (Gleick, 1994). Uranium ore extracted by traditional mining is chemically separated from other materials at a uranium mill and converted to yellowcake (U_3O_8). In-place extraction yields yellowcake directly. The yellowcake is then converted to uranium hexafluoride (UF_6) or uranium dioxide (UO_2). At this point, uranium is enriched. Naturally occurring uranium contains about 0.72 percent uranium-235 (the remainder is uranium-238, which is non-fissile). To increase energy content, the relative amount of uranium-235 must be increased to

Acid mine drainage in an open limestone channel near Huntsville, Missouri.

3–4 percent. Enrichment has historically been done by a gas-diffusion process; most newer enrichment facilities use gas centrifuges arranged in cascading series. The final processing step is fabrication of the fuel rods from the enriched uranium.

Uranium mining in the United States began in earnest in the 1940s. Annual production has varied substantially over the years, mostly in response to economics. Annual production in 2013 was about 2,080 metric tons of U_3O_8, a substantial decrease from the highpoint of 1980, when 16,810 metric tons were produced. Since the 1990s, most of the uranium used in the United States is imported from other countries. A total of 10 uranium mines were operating in the United States in 2013. Seven of these mines used in-place leaching; the other three active mines were traditional underground mines (U.S. Energy Information Administration, 2014c). Only one uranium mill, for processing ore from traditional mines, was operational in the United States in 2013.

Water Use

Water is used in all steps of uranium extraction and processing. Similar to coal mining, traditional uranium mining at underground or surface mines requires water for dust control, equipment washing, remediation, and revegetation. In-place leach mining (fig. 9) has different water needs. In-place leach mining uses a series of injection and extraction wells: water and chemicals are injected into an aquifer, the mixture dissolves the uranium, and the groundwater is pumped to the surface, where the uranium is removed. The process is repeated until uranium can no longer be economically recovered. Estimates of water consumption for mining and milling from traditional surface and underground mines in Australia, Africa, and North America ranged from about 400 to 800 L-water/kg of yellowcake in 2005 (Mudd and Diesendorf, 2008). This same study found that a single in-place leach mine required about 8,800 L-water/kg of yellowcake. The higher water consumption with in-place leach mining is largely related to production and subsequent evaporation of waste sludge and wastewater. Mudd and Diesendorf (2008) also noted that lower grade ore deposits require more water for processing. Conversion of yellowcake to UF_6 or UO_2 (depending on the type of reactor) consumes about 10,000 L-water/kg of 3.5-percent enriched uranium, whereas enrichment by gas centrifuges consumes about 5,100 L-water/kg of enriched uranium (Gleick, 1994). The final step in fuel processing, fabrication of fuel rods, consumes an estimated 2,500 L-water/kg of enriched uranium (Gleick, 1994).

Spent fuel and other radioactive by-products can be re-processed for reuse, thereby garnering additional thermal heat, but large quantities of water are required for this process—estimates are as high as 130,000 L-water/kg of enriched uranium (Gleick, 1994). Commercial reprocessing is not currently being done in the United States, but it is done in several countries, including France, the United Kingdom, Russia, and, more recently, China.

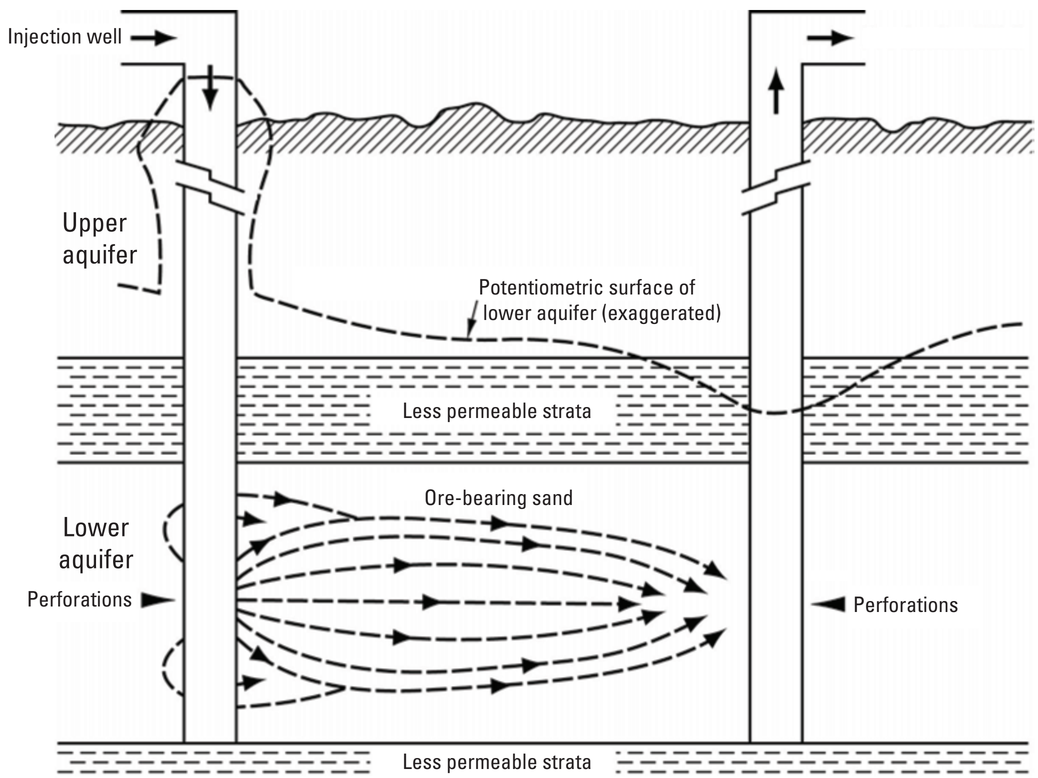

Figure 9. In-place recovery of uranium using chemical leaching compounds. Dashed, arrow-tipped lines show hypothetical flow paths of injected leaching solutions in the subsurface. (From U.S. Nuclear Regulatory Commission, 1997)

Water Quality

Potential contamination of water resources from extraction and processing of uranium continues to be an issue of concern, primarily at mining and milling sites. Although only a small number of domestic mines and mills are currently active, uranium-related activities since the 1940s have left a legacy of abandoned mines and mills across some western States. Many of these sites continue to contaminate air and water resources. It is estimated that there are 4,000 uranium mines in the states of Wyoming, New Mexico, Utah, Colorado, and Arizona that are no longer in production. These mines, as well as many abandoned mills, are current or potential sources of water contamination. Acid-mine drainage, similar to that described for coal mining, and contamination of water supplies by uranium, radium, and other radionuclides are the most important concerns from a water resources perspective (U.S. Environmental Protection Agency, 2013a). Although in-place leach mining causes little surface disturbance and leaves no tailings, it still generates waste products. If not properly managed, in-place mining can lead to groundwater contamination.

Uranium mine and tailings, Emery County, Utah.

Biomass

The term "biomass" refers to renewable fuels that are produced from plants and animals. This category can be broken down according to fuel use: those used for transportation and those used to generate electricity and heat. Transportation fuels are referred to as "biofuels," and fuels used for electricity and heat are "wood and waste." The two most common biofuels are bioethanol and biodiesel. These fuels are used as replacements for or additives to gasoline and diesel fuel. "Wood and waste" refer to wood and biogenic wastes or byproducts from agricultural, industrial, and municipal processing. Wood is the most prominent biomass fuel; it has traditionally been used to heat homes and other buildings and is still used for this purpose. In 2013, it accounted for about 23 percent of all renewable energy used in the United States, more than bioethanol and biodiesel combined (U.S. Energy Information Administration, 2014b). About 30 percent of wood consumption in that year was for home and commercial heating and about 70 percent was for generating electricity and providing heat for industry. Because wood is not grown commercially as a fuel, irrigation is not a source of water consumption. Small amounts of water may be required for processing of raw wood (such as for making wood pellets) prior to being consumed, but these amounts are generally inconsequential. As such, the remainder of this section addresses production and processing of biofuels.

Production of biofuels has increased steadily over the past decade, both within the United States (fig. 10) and worldwide. In 2013, about 55 billion L of biofuel were produced within the United States, about 5 percent of all domestic transportation fuels (U.S. Energy Information Administration, 2014b). A number of factors have played into the heightened interest in biofuels—national security (the desire to reduce the Nation's energy dependence on other countries), a desire for lower energy costs, and a desire to reduce the carbon footprint of traditional hydrocarbon transportation fuels. Biofuel production within the United States is largely driven by the U.S. Energy Independence and Security Act of 2007 (EISA), which called for 34 billion L of renewable fuels by the year 2008 (38 billion L were actually produced) and 136 billion L by the year 2022. Europeans have set similar goals, with renewable fuels required to account for 10 percent of all transportation fuels by the year 2020 (European Union Commission, 2009). Brazil, the second largest producer of biofuels behind the United States, requires that all gasoline be blended with ethanol at ratios of 3:1 (E25) to 4:1 (E20) (U.S. Energy Information Administration, 2013a).

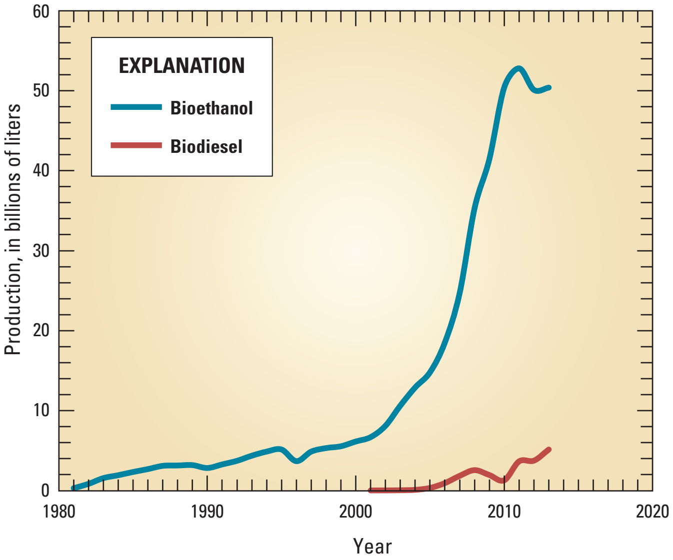

Figure 10. Annual production of biofuels in the United States, 1981–2013. (Data from U.S. Energy Information Administration, 2014b)

Water is required for growing the raw material (referred to as feedstock) used to produce biofuels and for converting the feedstock to fuel at refineries. Crop water requirements vary substantially depending on feedstock, climate, and soils. Many crops thrive on natural precipitation in humid and subhumid regions of the United States, whereas irrigation may be required in more arid regions. We only consider applied irrigation water in estimating water consumption rates for growing biofuels. In addition, agricultural chemicals such as fertilizers and pesticides are often applied to enhance production rates; these chemicals can potentially lead to contamination of surface water and groundwater (Gilliom and others, 2006; Dubrovsky and others, 2010).

Water Use for Bioethanol

Sugar and starch crops currently (2014) constitute the largest feedstocks for bioethanol production, with corn being the most popular fuel source in the United States and sugarcane in Brazil. On the basis of energy content and water requirements, it is widely accepted that corn is not the optimal fuel source for bioethanol production (U.S. Environmental Protection Agency, 2014d). Corn is currently being used in the United States because farmers have a great amount of experience growing corn and because techniques for converting grain to ethanol are well understood. The U.S. Congress, however, acknowledged the limitations for corn-based ethanol production; it mandated in the EISA that 58 percent of the 136 billion L of biofuel produced in 2022 be derived from cellulosic material (such as perennial grasses and wood) or other non-corn feedstocks. The reasoning was two-fold: to promote the most efficient fuel sources and to avoid the competition for grain between food and energy interests. Corn and sugarcane are referred to as “first generation” feedstocks; water requirements for growing and processing these crops are well known because operations are currently active. Less understood are the water requirements for “second generation” cellulosic feedstocks such as the perennial grasses switchgrass (*Panicum virgatum*) and miscanthus because these crops have not been grown in large-scale farms and refining techniques are still under development.

Irrigation accounts for most water consumption in bioethanol production. Water requirements for corn depend on climate, soil, landscape, and growth stage of the plant, but corn typically requires 400–650 millimeters (mm) of water during the growing season (Wu and Chiu, 2011). Corn can be grown without irrigation in much of the eastern half of the United States where the climate is subhumid to humid, but irrigation is sometimes used in these regions if water is readily available. In the more arid western regions of the United States, it is difficult to grow corn without irrigation.

Approximately 50 billion L of ethanol were produced in the United States in 2013 (U.S. Energy Information Administration, 2014b), consuming about 4.7 billion bushels of corn, roughly 34 percent of the total corn harvest of 13.9 billion bushels. The amount of land planted in corn has generally increased since the year 2000 (fig. 11), mirroring the price of corn. The increased acreage includes the addition of new crop land as well as the conversion of existing crop land from other crops to corn. The amount of irrigated corn acreage also increased between 2002 and 2007, though the percentage of corn acreage under irrigation remained relatively constant at about 12 percent (U.S. Department of Agriculture, 2010). The total amount of water withdrawn for corn irrigation increased only slightly from 14.4 trillion L in 2002 to 14.8 trillion L in 2007; more land was put under irrigation, but the actual amount of applied water increased only by about 2 percent.

Water consumed in growing corn for ethanol can be estimated with the numbers provided in the previous paragraph by making a few simple assumptions. We assume that irrigation rates for 2013 were similar to those for 2007 (the most recent year for which data are available [U.S. Department of Agriculture, 2014]) and that 40 percent of the water withdrawn for corn irrigation can be allocated to ethanol production. Following the approach of Wu and others (2009) and Wu and Chiu (2011), we also assume that 71 percent of that water is consumed by the crop (the remaining 29 percent is returned to the biosphere) and that 67 percent of the consumed water is allocated to ethanol (the remaining 33 percent is allocated to co-products generated by refinery operations). Under these assumptions, the water consumption rate for growing corn for ethanol in 2013 is about 56 L of water per L of ethanol (L-water/L-ethanol), similar to the estimate of Wu and Chiu (2011) of 51 L-water/L-ethanol for three corn growing regions of the United States in 2008.

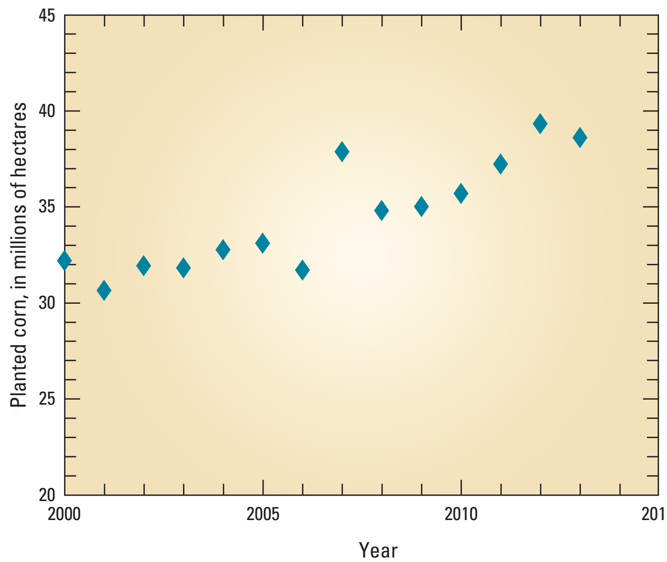

Figure 11. Annual hectares of planted corn in the United States, 2000–2013. (From U.S. Department of Agriculture, National Agricultural Statistics Service, 2014)

The conversion of corn and other grains to bioethanol at refineries also requires water. Most water used in the refinery is used for cooling, although water is also used for feedstock preparation and fermentation. Refineries have reduced the amount of water needed to produce ethanol since the early models of the late 1990s. Early refineries used as much as 11 L-water/L-ethanol (Shapouri and Gallagher, 2005), whereas average withdrawal and consumption for 2008 were reported to be 2.7 L-water/L-ethanol and 2.3 L-water/L-ethanol, respectively (Mueller, 2010). These water-use numbers are small relative to those for irrigation, but refinery water requirements can be significant on a local level. As of November 2013, there were 210 bioethanol refineries in operation within the United States with a total bioethanol production capacity of 56 billion L/yr (Renewable Fuels Association, 2013). The average bioethanol production capacity per plant is about 266 million L/yr. At a water withdrawal rate of 2.7 L-water/L-ethanol, about 720 million L of water per year are required on average for each plant.

Attaining the EISA goal for production of 60 billion L of cellulosic bioethanol by the year 2022 faces significant challenges. The technology for large-scale conversion of cellulosic material to ethanol is still under development; there were no commercial refineries that could do the conversion operating in the United States in 2013. In addition, cellulosic feedstocks would soon need to be grown on a large scale. Perennial grasses such as switchgrass and miscanthus have been suggested as possible feedstocks—fields of miscanthus can produce about 10,000 L of ethanol per hectare without irrigation, yields almost 50 percent higher than those for corn (Extension, 2014). However, conversion of large amounts of farmland from a traditional corn/soybean rotation to perennial grasses may be difficult. To produce 60 billion L of ethanol with current technology, at least 6 million hectares of farmland will need to be planted in perennial grasses. Six million hectares represent about 15 percent of all land planted in corn in the United States in 2013. Farmers will face logistical as well as cultural difficulties adapting to such a large-scale change in farming practices. In light of these uncertainties, it is not possible to predict water requirements for production of cellulosic bioethanol.

Perennial grasses such as switchgrass and miscanthus have qualities that make them potentially well suited for use as feedstock. These grasses have a high resistance to pests and low fertilizer requirements, and they can tolerate droughts as well as floods. Different varieties of these grasses grow in all areas east of the Rocky Mountains (Extension, 2014).

Water Use for Biodiesel

Biodiesel is a fuel made from natural oils and greases that can be used as a replacement for traditional diesel fuel. In 2013, approximately 5.1 billion L of biodiesel were produced in the United States (U.S. Energy Information Administration, 2014b). Soybean oil accounted for about one half of the feedstock; the other half consisted of a mixture of other vegetable oils (such as canola, cottonseed, and palm) and animal fats. Production of biodiesel in the United States has followed a general upward trend since 2000 (fig. 10). In 2013, roughly 10 percent of all soybeans grown in the United States were converted into biodiesel.

The amount of water consumed in developing biodiesel cannot be accurately determined because of the many different types of feedstock. As with bioethanol, the largest water requirement for biodiesel pertains to irrigation of the feedstock crops. In 2007, 2.8 million hectares of soybeans were irrigated in the United States with a total amount of 6 trillion L of water (U.S. Department of Agriculture, 2010). If we assume that biodiesel feedstocks have the same water and irrigation requirements as soybeans, then 10 percent of the water used for irrigation of soybeans can be allocated to biodiesel production. If we further assume, as with bioethanol, that irrigation rates for 2013 were similar to those of 2007, that 71 percent of irrigation water is consumed by the crop, and that 67 percent of that irrigation is allocated to biodiesel (the remaining 33 percent is allocated to refinery byproducts), it follows that the production of 5.1 billion L of biodiesel in 2013 consumed about 290 billion L of water or about 57 L-water/L-biodiesel. Biodiesel refineries typically consume 1 to 3 L-water/L-biodiesel (Pate and others, 2007).

Future trends in biodiesel production largely depend on development of new feedstocks. Research efforts are currently underway to improve techniques for producing oil from algae, with the hope of developing economically viable commercial operations. The potential rewards of developing this algae feedstock are substantial. Whereas a hectare of corn can produce up to 5,200 L of ethanol, and a hectare of soybeans can produce 840 L of biodiesel, a hectare devoted to algae has the potential to produce 9,400–59,000 L of biodiesel (Chisti, 2008). In addition, algae can grow with water of marginal quality. Because no commercial algae/oil production plants are operational, however, water requirements are unknown.

Water Quality and Biofuels

Growing crops for biofuel production raises some water-quality concerns. Corn requires substantial amounts of nitrogen to grow, as much as 0.45 kg per bushel of yield per year. Pesticides such as acetochlor, atrazine, and glyphosate are commonly used to control weeds in corn fields. Surface water and groundwater in much of the central United States have become contaminated with high levels of nitrates and pesticides (Gilliom and others, 2006; Dubrovsky and others, 2010). Watersheds in the upper Midwest contribute substantial amounts of nitrogen to streams. Annual nitrogen loads for the reaches of the Iowa River for 2004 and 2008 were between 400 and 6,800 kg per square kilometer of contributing drainage area (Garrett, 2012), and from 1985 through 2012, annual discharge of nitrogen to the Gulf of Mexico ranged from 0.7 to more than 2.2 million metric tons (U.S. Geological Survey, 2013). The transition from corn to cellulosic feedstocks, however, may eventually lead to some reduction in nitrogen and pesticide contamination of the Nation's water resources. Unlike corn, soybeans do not require application of nitrogen fertilizers (though they are commonly treated with pesticides and other fertilizers).

Water contamination from bioethanol and biodiesel refineries has not been widely reported. Indeed, there is usually little waste from these refineries. Byproducts such as distillers dried grain and solubles (DDGSs) are used for animal feed and other purposes, and other byproducts can be combusted and used to provide heat or to generate electricity to sustain refinery operations (Wu and Chiu, 2011).

Electrical Power Generation

Generation of electricity accounts for about 40 percent of all energy consumption in the United States. Most forms of electricity generation also consume water, much more water, in general, than other energy development activities. The previous section discussed water requirements for different fuels, many of which are used to generate electricity. This section examines water withdrawal and consumption and water-quality issues associated with power plants that generate electricity. Water consumption is presented in terms of water intensity, in units of liters of water consumed per generated kilowatthour of electricity (L/kWh). A less water-intensive process consumes less water to generate a unit of electrical power.

The availability of water is fundamental to most electricity generation. For example, hydroelectric power plants use the energy of falling water to drive turbine generators, and thermoelectric power plants require water for cooling and condensing the steam used to drive turbine generators. Water use for thermoelectric plants constitutes the single largest withdrawal of water in the United States; in 2010, thermoelectric power generation accounted for about 45 percent of all freshwater withdrawals (Maupin and others, 2014). Wind and solar photovoltaic power plants, on the other hand, are somewhat unique in that they generate electrical power with relatively small water requirements; these plants are growing in popularity but still constitute a small portion of the total electrical power capacity in the United States (fig. 12).

Thermoelectric Power Plants

Thermoelectric power plants generate about 89 percent of the electricity in the United States (U.S. Energy Information Administration, 2014b). As the name implies, these plants convert thermal energy to electrical energy, mostly through the use of steam turbines. Water is boiled within a closed system to create steam, and the steam drives the turbine generators that create electricity. After passing through the turbine generators, the steam is cooled and condensed back to liquid form, and the water is reused in the cycle. The cooling process accounts for more than 90 percent of all water withdrawal and consumption at most plants. Thermoelectric plants are fueled primarily by coal, natural gas, and nuclear energy (fig. 12). Other thermoelectric plants, powered by geothermal or solar energy, are important on a regional basis but account for less than 1 percent of generated electricity on the national scale.

Water Use for Thermoelectric Plants

Water use in electricity generation is controlled primarily by three factors:

- *Energy content of fuel used in the process*—Energy content refers to the energy released or available when a unit mass or volume of fuel is consumed. The concept is identical to the calorie content of foods we eat: calories are a measure of energy, and foods are fuel for the human body. Energy contents for selected fuels are shown in table 2.
- *Type and thermal efficiency of the power plant*—Thermal efficiency refers to the ratio of electrical energy produced in a power plant to the heat or thermal energy of the fuel that is consumed in the process.
- *Type of cooling system that is used*—Most cooling systems rely on water to dissipate heat, but air can also be used.

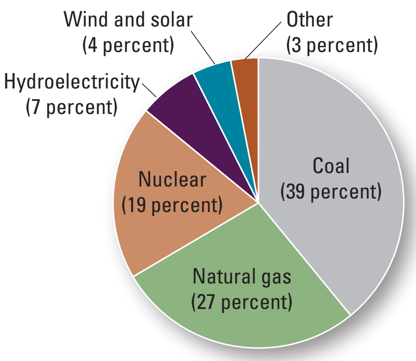

Figure 12. Total electricity generation in the United States by fuel, 2013. "Other" includes biomass, oil, waste incineration, and geothermal power. (Data from U.S. Energy Information Administration, 2014b)

Table 2. Energy contents of selected fuels.

[kWh_{th}, kilowatthours of thermal energy; kg, kilogram; m^3, cubic meter; L, liter]

Fuel	Energy content
Coal—bituminous	7–9.7 kWh_{th}/kg
Coal—subbituminous	5.3–8.3 kWh_{th}/kg
Coal—lignite	3.6–5.3 kWh_{th}/kg
Natural gas	10.6 kWh_{th}/m^3
Wood	4.5 kWh_{th}/kg
Fuel oil	10.6–11.8 kWh_{th}/L
Uranium-235	2.3×10^7 kWh_{th}/kg
Gasoline	8.9 kWh_{th}/L
Diesel	10 kWh_{th}/L
Bioethanol	5.1–5.9 kWh_{th}/L
Biodiesel	9.3–9.9 kWh_{th}/L

Power Plant Thermal Efficiency

Thermal efficiencies of thermoelectric power plants vary with plant type and fuel (table 3). For example, coal-fired steam-turbine plants typically have an efficiency of about 34 percent. In other words, about 34 percent of the energy stored in coal is converted into electrical energy; the remaining 66 percent of the thermal energy is used for plant operations, transferred to the cooling water, or lost through the smokestack. In addition to steam turbines, electricity can be generated by combustion turbines and combined cycle systems. Combustion turbines (sometimes referred to as gas turbines) are driven directly by the combustion of natural gas. They are typically run for short periods of time to meet peak demands for electricity and require no cooling water. They accounted for about 3 percent of electricity generation in the United States in 2012 (U.S. Energy Information Administration, 2013b). Thermal efficiency of combustion turbines, about 30 percent (Scanlon and others, 2013), is less than that

Table 3. Power plant thermal efficiency and water consumption rates for different types of electricity generation in terms of water intensity (in liters of water per kilowatthour of generated electricity).

[L/kWh, liters of water per kilowatthour of electricity; na, not applicable; --, unknown]

Plant type	Thermal efficiency (percent)	Cooling process	Range of reported power plant water consumption rates (L/kWh)
Coal—steam turbine	[1]34	Once-through	[2,8]0.2–1.2
	[1]34	Tower	[2,8]1.6–2.5
Nuclear—steam turbine	[1]33	Once-through	[3]0.4–1.5
	[1]33	Tower	[3]2.2–3.4
Natural gas—steam turbine	[1]33	Once-through	[3,8]0.7–1.7
	[1]33	Tower	[3]2.1–4.2
Natural gas—combined cycle	[1]45	Once-through	[3]0.1–0.9
	[1]45	Tower	[3]0.2–1.1
Natural gas—combustion turbine	[9]30	na	na
Biomass	[10]24	Tower	[2]1.8–3.6
Geothermal (binary)	[4]8–16	Tower	[5]6.8–9.9
Geothermal (flash)	--	na	[6]3.3
Concentrating solar power (parabolic trough)	--	Tower	[3]2.1–7.2
Hydroelectric	--	na	[7]3.5

[1]U.S. Energy Information Administration (2012a).

[2]Macknick and others (2012).

[3]Meldrum and others (2013).

[4]DiPippo (2007).

[5]Mishra and others (2011).

[6]Adee and Moore (2010).

[7]Value for hydroelectric power is for reservoir evaporation from example in this report.

[8]Diehl and Harris (2014).

[9]Scanlon and others (2013).

[10] Wiltsee (2000).

for gas steam turbines. Combined-cycle natural gas power plants have two electricity-generating cycles: the first cycle uses a combustion turbine, and the second cycle captures the exhaust from the combustion turbine and uses it as the heat source for a steam-driven turbine. Combined-cycle natural gas power plants have an average thermal efficiency of 45 percent (table 3).

Other factors can affect power-plant thermal efficiency, including demand for electricity, air temperature, and ambient cooling water temperature. As a result, thermal efficiency varies with climate and location, as well as with season and time of day. Thermoelectric power plants are least efficient during summer months because warmer air and water temperatures make it difficult to cool the system. In addition, peak electrical demands often occur in summer months because of heavy air conditioner use (fig. 13). Increased electrical demand and decreased thermal efficiency mean that water consumption at any thermoelectric power plant is usually highest in summer months.

Thermal efficiency of power plants is linked to water intensity in complex fashions. For water-cooled systems, the amount of cooling water required varies with the amount of fuel consumed. If the amount of fuel consumed per kilowatt-hour of electricity is reduced, then less water is consumed. At the same time, more effective cooling can enhance thermal efficiency.

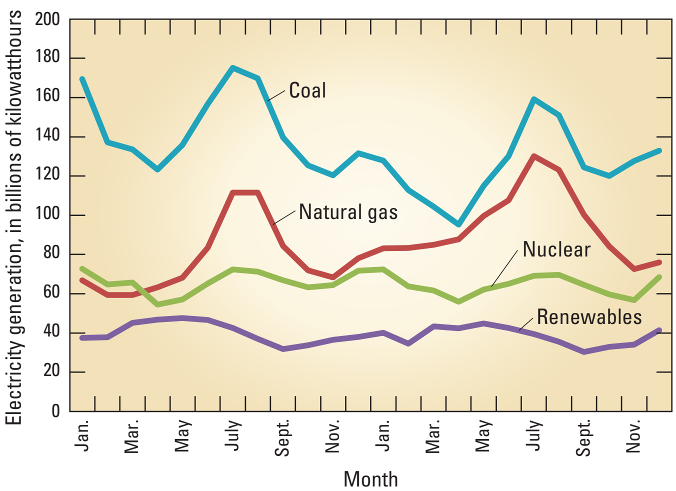

Figure 13. Monthly net electricity generation in the United States by source, January 2011–December 2012 (U.S. Energy Information Administration, 2014b). Coal- and gas-generated electricity show distinct seasonal trends, with the highest rates of power generation in summer months and secondary highs in winter months. (Renewables include hydroelectricity, wind, biomass, solar, and geothermal.)

Power Plant Cooling Systems

The three general types of cooling systems are once-through (also known as open-loop), wet recirculating (also known as closed-loop), and dry. In once-through cooling systems water is withdrawn from a surface-water body, circulated through the system to absorb heat, and then discharged back into the surface-water body (fig. 14). The availability of large volumes of water is essential to the operation of once-through systems. These systems have relatively high rates of water withdrawals, but most of the withdrawn water is returned to the surface-water body, albeit at temperatures several degrees warmer than ambient conditions. Once-through systems have relatively low rates of onsite water consumption, but additional consumption of water occurs offsite. The warmer temperature of the discharged water promotes increased or "forced" evaporation downstream in the original water body (Diehl and others, 2013). Onsite water consumption can be monitored with meters, but there is no direct way to measure the amount of water consumed offsite as forced evaporation. See Diehl and others (2013) for a thermodynamics-based technique for estimating forced evaporation from power plant cooling systems.

The Federal Water Pollution Control Act of 1972 and recent regulations issued by the U.S. Environmental Protection Agency (2014c) placed restrictions on the use of once-through cooling systems for new power plants because of concerns about environmental effects. As a result, most thermoelectric plants installed since the mid-1970s are equipped with a wet recirculating cooling system, a closed-loop system in which water is circulated through the cooling system to absorb heat, the water itself is then cooled, and that water is recirculated (fig. 14). These cooling systems have relatively low rates of water withdrawal, but most of the water withdrawn is consumed through evaporative loss, resulting in higher water consumption than once-through systems. Tower-based systems account for about 85 percent of the electricity produced with recirculating systems, and the remaining systems use cooling ponds (Diehl and Harris, 2014). Small ponds consume water at rates similar to tower systems, whereas large ponds resemble once-through systems in their water consumption. A fraction of the water being recycled through a recirculating system must be discharged to prevent salts from reaching concentrations that cause scaling problems. This water is called "blowdown." The water that is withdrawn to replace evaporative losses and blowdown is known as "make-up water." Wet recirculating cooling systems using cooling towers typically consume about 30 to 70 percent more water per kilowatthour of electricity produced than once-through cooling systems (table 3) (T.H. Diehl, U.S. Geological Survey, written commun. 2013).

Dry cooling systems rely on heat exchange with ambient air, rather than water, for cooling; water withdrawal and consumption, therefore, are minimal for these systems. However, dry cooling is not as effective as wet cooling and can result in significant thermal efficiency and energy capacity penalties during hot weather conditions. To address these limitations, hybrid wet/dry systems are being researched and developed. Hybrid systems commonly involve separate dry and wet units installed in parallel. The wet system may operate only on the hottest days to evaporatively cool the air going to the air-cooled condenser. In the United States, approximately 43 percent of thermoelectric generating capacity uses once-through cooling, 42 percent uses wet recirculating with cooling towers, 14 percent uses wet recirculating with cooling ponds, and 1 percent uses dry cooling (National Energy Technology Laboratory, 2011).

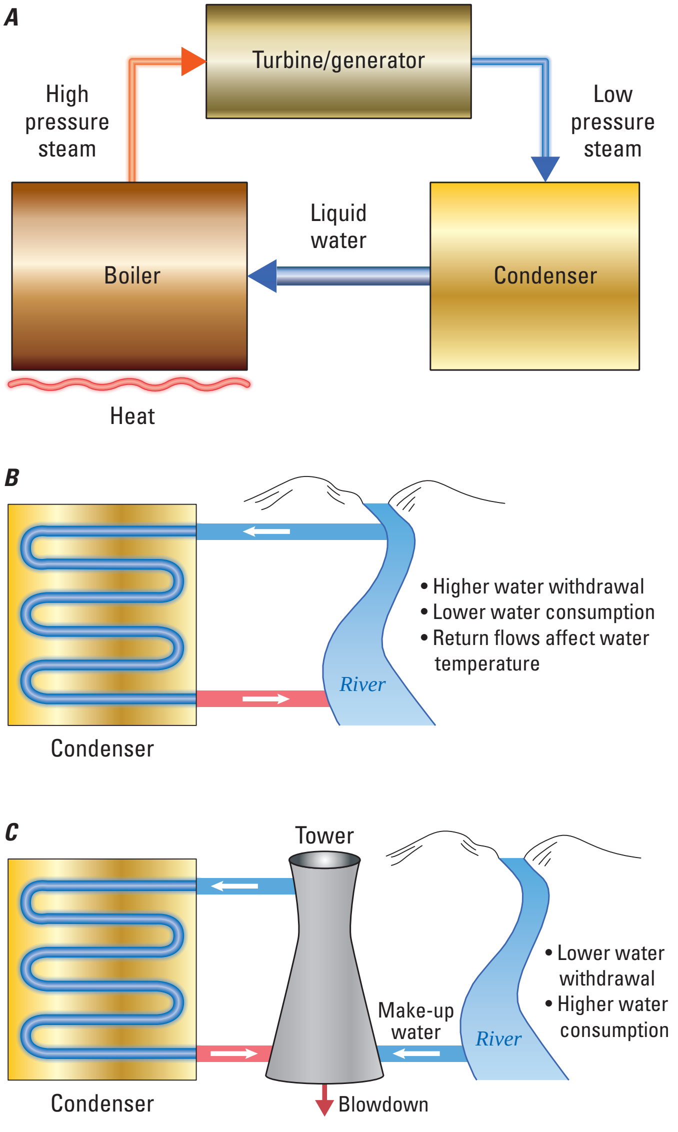

Figure 14. Schematic and general characteristics of (*A*) a steam thermoelectric power plant with water cooling, (*B*) a once-through cooling system, and (*C*) wet recirculating systems with cooling towers. Boiler water is contained in a closed system and does not mix with cooling water.

Water Withdrawal

Approximately 222 trillion liters of water were withdrawn in 2010 by thermoelectric power plants (Maupin and others, 2014), but not all of that water was consumed. As previously defined, water withdrawal refers to the amount of water extracted from a surface-water or groundwater source, and water consumption refers to that portion of withdrawn water that is evaporated or otherwise removed from readily accessible water resources. In the case of thermoelectric power generation, most water consumption occurs as evaporation from cooling systems. Cooling water that is not consumed typically is returned to the original water body. The amount of water consumed in a process is equal to the difference in the amount of water withdrawn and the amount returned. Thus, while thermoelectric power generation accounts for the largest total water withdrawals in the United States, its water consumption rate is much less than that of other uses such as irrigated agriculture (Solley and others, 1998; Kenny and others, 2009; Maupin and others, 2014).

Water withdrawals for thermoelectric power generation vary by location and plant design. Eastern states accounted for about 86 percent of total withdrawals in 2010 (fig. 15) and 75 percent of the related net power generation (Maupin and others, 2014). Most of these withdrawals are associated with thermoelectric power plants that use older, once-through cooling systems. Newer, wet recirculating cooling systems withdraw much less water. Most withdrawals for thermoelectric power are from surface water, but some southwestern States, where surface water is relatively scarce, tap groundwater for a substantial portion of their water withdrawals for thermoelectric power, including Nevada (89 percent), Arizona (74 percent), Utah (43 percent), and New Mexico (18 percent).

Concerns about water availability have led to greater use of degraded water sources for cooling and other thermoelectric power plant needs. Challenges in using these sources include the treatment needed to meet plant operation and regulatory discharge requirements and the potential for long transport distances from water sources. About 29 percent of total water withdrawals for thermoelectric power generation come from saline water along coastal areas, particularly California, Florida, and the Northeast (fig. 15). At least 50 power plants in the United States use treated municipal wastewater (reclaimed water) for cooling and other purposes; Florida and California have the largest number of plants that use reclaimed water (Veil, 2007).

The average amount of water withdrawn to produce a kilowatthour of electricity in the United States has decreased steadily from about 240 L in 1950 to about 72 L in 2010 (Maupin and others, 2014). This trend is attributed to decreased use of once-through cooling systems, more efficient cooling technologies, and increased thermal efficiency of power plants. Looking toward the future, electrical power consumption will likely increase, but freshwater withdrawals by power plants are projected to decrease as greater use is made of wet

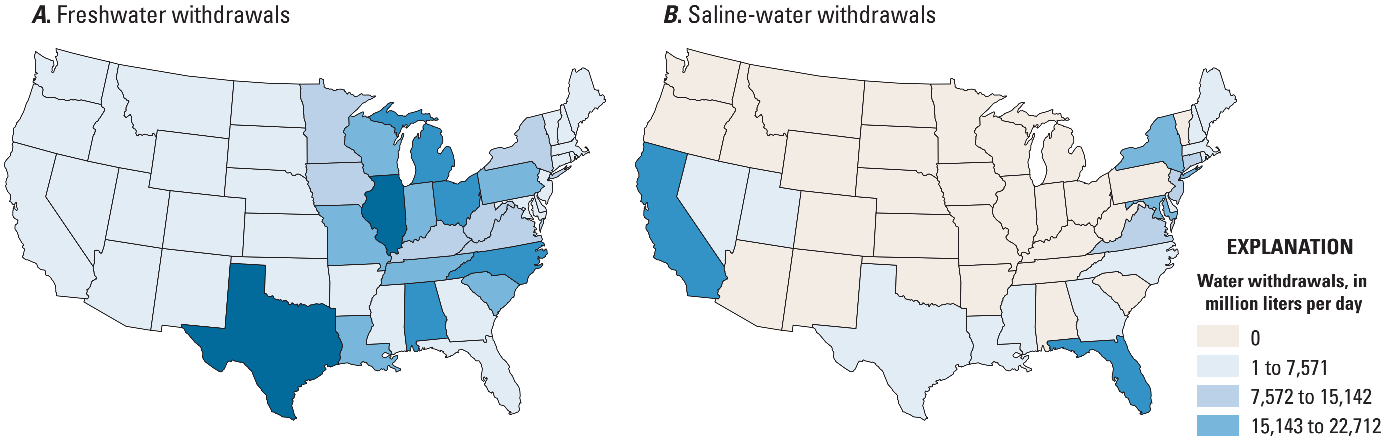

Figure 15. Freshwater and saline-water withdrawals for thermoelectric power generation by State, 2010. (Modified from Maupin and others, 2014)

recirculating cooling systems (National Energy Technology Laboratory, 2011).

Water Consumption—Carbon-Fuel and Nuclear Plants

Thermoelectric power plants consume large amounts of water, but exactly how much water is a matter of some uncertainty. Estimated rates of water consumption by power plants vary considerably (National Energy Technology Laboratory, 2006; Macknick and others, 2011, 2012; Diehl, 2012; Diehl and others, 2013; Meldrum and others 2013; Diehl and Harris, 2014), largely because of a lack of standardized water-accounting methods. Here we present a broad survey of values reported in the literature for water intensities for electricity generation at thermoelectric power plants. A much more detailed investigation based on thermodynamic constraints is provided by Diehl and Harris (2014) for power plant water intensities in 2010.

Coal-fired power plants produce more electricity in the United States than any other type of plant—the 1.6 trillion kWh of electricity generated from coal in 2013 represents 39 percent of total electricity generation in the country. The dominance of coal-fired plants in the United States, however, has declined in recent years (fig. 16) as more natural gas–fired plants have come on line. Steam turbines with once-through or recirculating cooling systems are used in most coal-fired power plants. Reported power plant water intensities for generating electricity from coal range from 0.2 to 1.2 L/kWh with once-through cooling and from 1.6 to 2.5 L/kWh with recirculating tower cooling (table 3).

Natural gas-fired thermoelectric power plants generated 1.1 trillion kWh of electricity in 2013, about 27 percent of total electricity generation. No cooling is required for combustion turbines, so water consumption rates for these systems are negligible. Water consumption rates for gas-fired steam-turbine power plants are slightly greater than those for coal-fired systems, ranging from 0.7 to 1.7 L/kWh with once through cooling and from 2.1 to 4.2 L/kWh with recirculating tower cooling (table 3). Water consumption rates for natural gas combined-cycle power plants are generally less than those for gas-fired or coal-fired steam systems because of the higher thermal efficiency of combined-cycle systems; they range from 0.1 to 0.9 L/kWh with once-through cooling and from 0.2 to 1.1 L/kWh with recirculating tower cooling.

Nuclear plants generate electricity with steam turbines, and the heat to produce the steam is provided by the splitting, or fission, of atoms of uranium-235. As of 2014, the 62 commercial nuclear power plants in the United States (fig. 17), comprising 100 reactors, were producing about 789 billion

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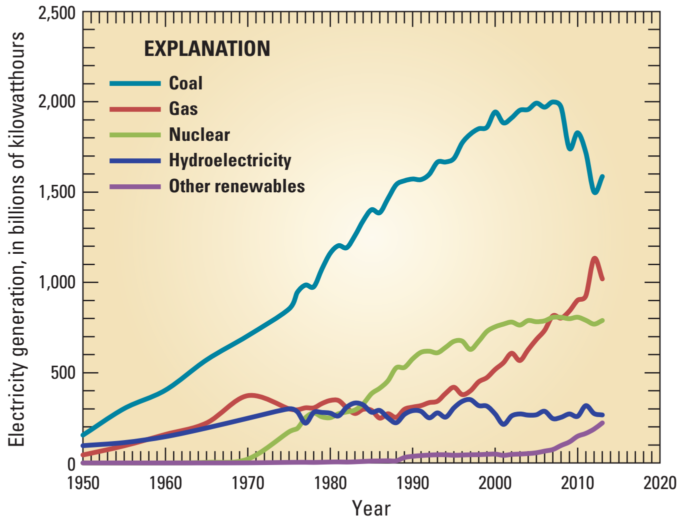

Figure 16. Annual electricity generation in the United States by fuel, 1950–2013. "Other renewables" include wind, biomass, geothermal, and solar power (U.S. Energy Information Administration, 2014b).

Droughts and Energy Development

Drought is a protracted period of below-normal precipitation. The effects of drought vary with region, climate, and human activities. Extended periods of drought can cause streams and reservoirs to dry up and groundwater levels to decline. The resulting effects can be severe, including loss of agricultural crops, destruction of aquatic ecosystems, wildfires, and implementation of municipal water-use restrictions. Energy operations can also be adversely affected by droughts.

Two things occur during droughts that can affect operations at thermoelectric power plants—reduced streamflow and increased stream temperature. Power production could be reduced as a result of limited water availability to satisfy all demands, including instream flow requirements. The drought of 2011 in Texas provides an example (Averyt and others, 2011). By late summer 2011, Texas had suffered the driest 10 months since record keeping began. Demand for electricity increased by 6 percent, which led to a 9 percent increase in water demand to produce this electricity (Scanlon and others, 2013). At the same time, storage in power plant cooling reservoirs decreased by 30 percent. The shores of Martin Creek Lake, the primary source of cooling water for the Luminant coal-fired power plant, receded to precariously low levels. In order to avoid a reduction in plant operations, a 14-km pipeline was constructed to import cooling water from the Sabine River (Scanlon and others, 2013).

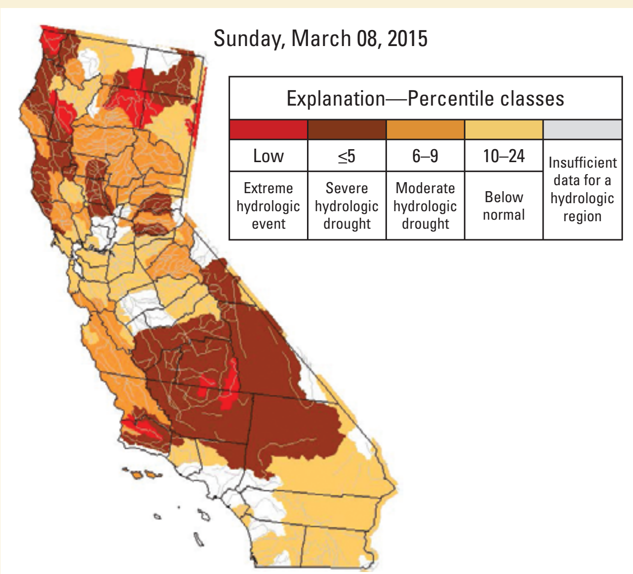

Figure I–1. An example of a drought index map developed on the basis of percentile of 7-day average streamflow relative to historical streamflow on a given day of the year (U.S Geological Survey, 2015). Other bases for drought indices include precipitation, such as the Palmer Drought Severity Index and the Standardized Precipitation Index (*http://droughtmonitor.unl.edu/), and soil and vegetation moisture (http://www.wfas.net/index.php/keetch-byram-index-moisture--drought-49*).

Power plant operating permits require that discharges of cooling water always be less than a certain maximum temperature in order to minimize adverse effects on fish and other aquatic life. Increased stream temperatures during droughts, combined with peak demands for electricity during summer months, can lead to situations in which plants must reduce power generation to avoid exceeding maximum discharge temperatures. During three summers from 2007 to 2011, the temperature of the Tennessee River rose above a 32 °C threshold, forcing reductions in power output from the Browns Ferry nuclear power station. (Averyt and others, 2011). In the summer of 2012, one of two reactors at the Millstone nuclear power plant near New London, Connecticut, was shut down when temperatures in Long Island Sound, the source of the facility's cooling water, reached their highest levels since the facility began monitoring in 1971 (Eaton, 2012). Likewise, the high temperatures of the Mississippi River during a 2006 heat wave forced the Prairie Island nuclear plant in Minnesota to cut its electricity generation by more than half (Averyt and others, 2011).

Electrical power grids in the United States have developed some resiliency over the years, and many new power plants are designed to consume less water than older plants. The droughts of recent years proved to be severe tests for electricity generators, but Americans received the power they demanded because providers were able to purchase electricity from alternative sources, albeit at higher costs for consumers.

The Browns Ferry nuclear power station in Tennessee was forced to reduce electricity generation for some summer months because of high water temperatures in the Tennessee River.

kWh of electricity per year, 19 percent of all electricity production in the country (Power Reactor Information System, 2014). Electricity production from nuclear power plants has been fairly steady since 1996 when the most recent reactor came on line (fig 16). Production is predicted to remain fairly steady through 2035, at which time nuclear power will account for about 18 percent of electricity generation (U.S. Energy Information Administration, 2012b). Production will likely decline after 2035, as many nuclear power plants will be near the end of their expected lifetimes and few new plants are currently under construction. In spite of the 2011 Fukushima Daiichi nuclear disaster in Japan, polls still show modest public support for continued development of nuclear power in the United States (Newport, 2012).

Water consumption rates for nuclear power plants range from 0.4 to 1.5 L/kWh with once-through cooling and from 2.2 to 3.4 L/kWh with recirculating tower cooling, ranges similar to those of gas-fired steam-turbine plants (table 3). The nuclear power industry, however, has some additional, unique water needs, even if the amount of water used is relatively small. Nuclear fuel rods continually generate heat, even if electricity is not being produced. For this reason, cooling systems are designed to constantly remove this "decay heat" from the plant with water. In addition, when spent fuel rods are removed from nuclear reactors, they must be immersed for five years or more in deep pools of water for cooling and for blocking radiation (Alley and Alley, 2013).

There are many small biomass thermoelectric plants in operation in the United States. Wood-fueled thermoelectric plants are common in densely forested areas of the United States, such as New England. Plants fueled by other biomass sources are common in intensely farmed regions, such as the Central Valley of California. A total of about 60 billion kWh of electricity was generated from these plants in 2013, about 1.5 percent of total electricity generation in the United States (U.S. Energy Information Administration, 2014b). The water intensity for generating electricity from biomass-fueled power plants is in the range of 1.8 to 3.6 L/kWh of electricity (Macknick and others, 2011), similar to that for coal-fired plants (table 3).

Advances in technology will likely result in improved overall power-plant thermal efficiency in the United States as old plants are retired and new ones are brought online. However, pollution-control efforts at coal-, natural gas–, and biomass-fueled thermoelectric plants will affect thermal efficiency and, therefore, water consumption rates. Techniques

Figure 17. Locations of the 100 operational commercial nuclear power reactors in the United States as of 2014. (World Nuclear Association, 2014)

The Palo Verde Nuclear Generating Station, located about 88 km west of downtown Phoenix, Arizona, is the largest nuclear power plant in the United States, serving approximately 4 million people. Located in the desert, Palo Verde is the only nuclear plant in the world that is not situated adjacent to a large surface water body. The facility evaporates water from the treated sewage of Phoenix and nearby municipalities to meet its cooling needs.

for removing contaminants such as carbon dioxide, mercury, and sulfur from atmospheric emissions lead to cleaner air, but they also reduce thermal efficiencies of power plants. Methods for capturing carbon dioxide from power-plant emissions, although not yet fully developed, will inevitably lead to reductions in power-plant thermal efficiencies and increases in the water intensity of electricity generation (Meldrum and others, 2013; Tidwell and others, 2013).

Water Consumption—Geothermal Plants

Geothermal energy is heat generated within the Earth's core. Most of that heat is produced by radioactive decay of naturally occurring elements such as uranium, thorium, and potassium (Duffield and Sass, 2003). Heat flows outward from the core toward the land surface. The amount of heat flow is fairly uniform worldwide, but there are areas of anomalously high heat flow, such as in the vicinity of active or geologically young volcanoes. In areas of high heat flow, energy can sometimes be economically harvested for human use. The primary use of geothermal energy is to drive turbines and generate electricity in power plants that serve a large market. Secondary uses for geothermal energy include providing direct heat to buildings, sidewalks, and other infrastructure located near geothermal heat sources.

Geothermal energy sources produced about 17 billion kWh of electricity in the United States in 2013, about 0.4 percent of the Nation's total electricity generation (U.S. Energy Information Administration, 2014b). Areas of current geothermal development in the United States are located within and to the west of the Rocky Mountains (fig. 18). On the basis of current technology, geothermal energy production in the United States is predicted to increase by about 4 percent annually through 2035 (U.S. Energy Information Agency, 2012b), although it will remain a relatively minor provider of electricity on the national scale.

Geothermal power plants extract hot geofluids[2] from wells drilled as deep as several kilometers and use the heat of the fluids to power electrical generators. Three types of geothermal systems are used to generate electricity: dry steam, flash, and binary, depending on the nature of the geofluids (Duffield and Sass, 2003). Dry steam and flash techniques can

[2]The term "geofluid" denotes steam or saline groundwater; the term is used to distinguish these fluids from fresh groundwater. Consumption of geofluids is not included in the accounting of fresh water resources because of the high salinity.

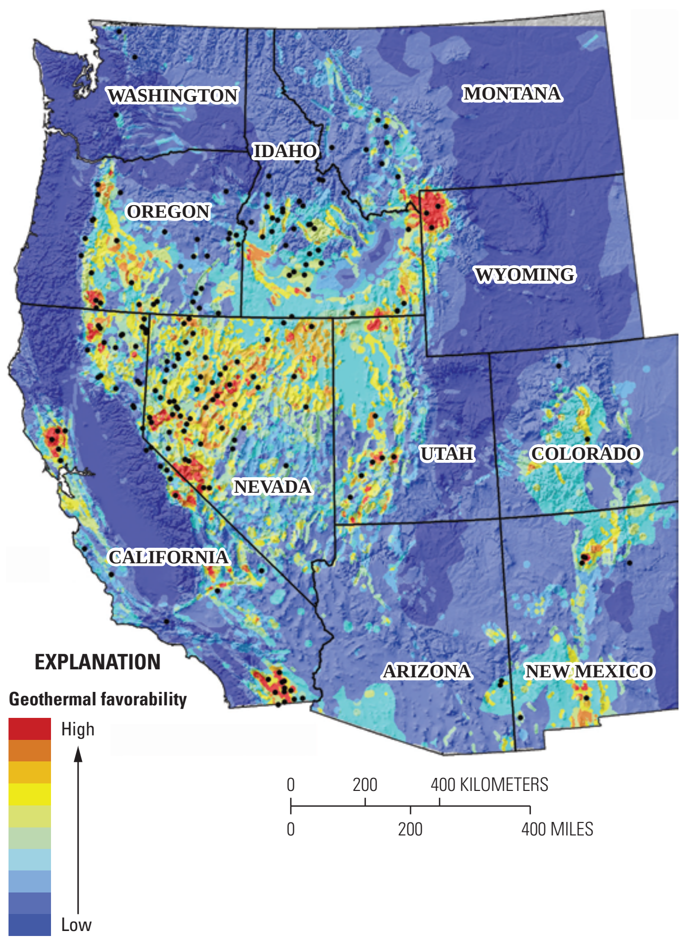

Figure 18. Relative favorability of occurrence of geothermal resources in the western contiguous United States. Identified geothermal systems are represented by black dots. (Williams and others, 2008)

be used when temperatures in the geothermal reservoir are generally between 175 and 300 °C; binary techniques usually are used when temperatures in the reservoir are less than 200 °C. In dry steam systems, the geofluid is in the form of steam, and in flash systems, liquid geofluids pumped to the geothermal plant immediately flash to steam. The steam in both systems is used to directly drive a turbine that generates electricity. In a binary system, the geofluid temperature is not sufficient to vaporize water instantaneously; instead, a second fluid with a lower boiling point than water is vaporized to drive the turbine. The largest geothermal power plants in the United States use dry steam or flash techniques.

The steam that passes through the turbines in dry steam or flash systems remains as steam or is condensed to liquid water; the steam is vented to the atmosphere, and any remaining condensate is injected back into the geothermal reservoir. Condensate may also be used for cooling, but in general these types of systems rely on dry cooling techniques. Fluids must be injected to the geothermal reservoir to maintain pressure, minimize induced seismic activity, and extend the life of the resource. Because about 70 percent of the original extracted geofluid mass is vented to the atmosphere as steam, this amount is typically made up with added water. Low-quality make-up water is acceptable for this purpose. For example, power plants at The Geysers geothermal field in northern California rely on treated municipal effluent for its make-up water. Small amounts of water are also needed at these plants for periodic flushing to avoid scale build up. Water intensity for California's 10 flash power plants averages about 3.33 L/kWh of generated electricity (Adee and Miller, 2010).

Water consumption rates at binary geothermal plants vary depending on the technique used to cool the binary fluid after it has passed through the turbine. About 78 percent of binary plants within the United States rely on dry cooling (Mishra and others, 2011) and therefore consume water at rates similar to those of flash power plants. In hot summer weather, though, air cooling is inefficient; the power output of a binary plant can be reduced by as much as 50 percent of its wintertime output. As a result, some plant operators augment dry cooling systems with closed-loop wet recirculating cooling systems that use a combination of geofluid condensate and make-up water (often freshwater). Binary plants also require make-up for injection into the geothermal source, and because dry cooled plants operate at a lower thermal efficiency than water-cooled plants, more geofluids are extracted per kilowatthour of generated electricity and more make-up water must be injected. Water intensity for electricity generation at binary geothermal power plants with wet recirculating cooling systems has been reported to range from 6.8 to 9.9 L/kWh (table 3; Mishra and others, 2011).

Water Consumption—Concentrating Solar Power Plants

Concentrating solar power (CSP) technologies rely on the sun as a heat source, using mirrors to focus the sun's energy on a small area. The technology has received considerable interest in recent years—30 States and the District of Columbia have established renewable portfolio standards that encourage the development of CSP technologies (U.S. Energy Information Administration, 2012c). In 2013, CSP plants in the United States generated about 926 million kilowatthours of electricity, much less than 1 percent of total electricity generation in the United States (U.S. Energy Information Administration, 2014a).

Most CSP technologies use mirrors to concentrate direct solar radiation onto a receiver tube in which a fluid is heated. The heated fluid is used to boil water for steam-driven turbine generators as in a traditional thermoelectric power plant. The heated fluid does not need to be used immediately; it can be stored and used to generate electricity at night or during cloudy weather. Unlike other types of thermoelectric power plants, a substantial amount of water is needed for the construction of CSP plants, in part because of the lower life span of CSP plants and the specialty chemicals that are required. Water consumption for plant construction is estimated at 0.6 L/kWh (Meldrum and others, 2013). Water is also used for cooling purposes, just as with other thermoelectric plants. Water consumption rates for CSP plants depend largely on the type of cooling system that is used. For parabolic trough plants, water intensity is estimated to range from 2.1 to 7.2 L/kWh (table 3; Meldrum and others, 2013). Parabolic trough CSP systems have operated in the California Mojave Desert for over 20 years.

Dish/engine or Stirling cycle CSP systems use a multi-mirrored dish that looks like a large satellite dish. The dish-shaped surface directs and concentrates sunlight onto a thermal receiver, which absorbs and collects the heat. This system uses the fluid heated by the receiver to move pistons and create mechanical power to run a generator or alternator to produce electricity. A distinct advantage of dish/engine

The Geysers geothermal field in northern California is the only dry steam system in the United States. It produces more power (about 950 MW on average) than any other geothermal plant in the world.

systems is that they use dry cooling. Thus, no water is needed other than for mirror washing. Unlike the other CSP systems, however, dish/engine systems do not lend themselves easily to thermal storage, so these systems provide electricity only when the sun is shining (U.S. Department of Energy, 2009).

Solar power is most effective in areas that have many hours of sunlight, such as the southwestern United States. Solar technologies such as CSP might improve power grid operations by providing energy when it is most needed during the hottest part of the day. It is estimated that CSP projects covering 1.4 percent of southwestern land could potentially generate as much power as is used in the entire United States (U.S. Department of Energy, 2009). Unfortunately, water is scarce in these same areas. In addition, some States such as California have placed restrictions on power-plant water use. As a result, CSP systems might require transport of water from distant sources, treatment of low-quality water such as municipal effluent, or use of dry or hybrid wet/dry cooling technologies.

Water Quality and Thermoelectric Power Plants

Water quality issues of electricity generation generally are related to contaminants emitted directly to the atmosphere from the fuel combustion, contaminants in the fuel residue that remains after combustion, and contaminants in water released to the environment. Power plants with once-through cooling systems place additional stress on water bodies and their ecosystems as a result of the temperature increases caused by return flows. Increased temperatures in streams can have deleterious consequences for aquatic life, especially during periods of drought when ecosystems are already stressed (Electric Power Research Institute, 2012). Large withdrawals for cooling also kill fish, larvae, and other organisms trapped against the intake structure (impingement) or drawn through the cooling system (entrainment). For steam-driven generators, the continual cycle of evaporation and condensation inside a boiler system leads to accumulation of salts and, therefore, a deterioration of water quality in boiler water. That water is occasionally flushed out, treated, and released to the environment (Diehl and Harris, 2014). The amounts of released boiler water are relatively small and generally have a minimal effect on water resources. Other issues are specific to fuel type.

Coal

Combustion of coal, gas, oil, and biomass emits carbon dioxide and other chemicals to the atmosphere. Carbon dioxide is a greenhouse gas that contributes to global warming. Other constituents that are released upon combustion, such as arsenic, mercury, sulfur oxides, nitrogen oxides, selenium, and additional trace elements, give rise to environmental and health concerns (see Box J—Energy, Atmospheric Emissions, and Water Quality). When gaseous or particulate pollutants are released to the atmosphere, surface-water and groundwater resources can be contaminated by rainfall or dry deposition.

The Ivanpah Solar Electric Generating System in the Mojave Desert of California can produce up to 392 MW of electricity.

Damage from the 2008 coal ash spill in Kingston, Tennessee.

Many coal-fired power plants in the United States have installed pollution abatement systems such as dust collectors and flue-gas desulfurizers (FGD) or scrubbers to capture contaminants before they are released to the atmosphere.

Power plants in the United States produced approximately 100 million metric tons of coal combustion residues in 2012 (American Coal Ash Association, 2014), equivalent to about 13 percent of the total mass of coal consumed. Residues, often referred to as coal combustion products (CCPs) or simply coal ash, consist of fly ash, bottom ash, boiler slag, and compounds from FGD systems. Fly ash is the residue captured in smoke stacks upstream of scrubbers, bottom ash is the residue that accumulates in the bottom of the burner, boiler slag is bottom ash produced in a certain type of boiler (wet-bottom boilers), and FGD compounds are those that are captured by the scrubbers. Fly ash, bottom ash, and slag consist mostly of silicon, calcium, aluminum, and iron oxides (Electric Power Research Institute, 2010), but they often contain potential environmental contaminants such as arsenic, mercury, selenium, and uranium. The chemical nature of the ash relates to the type of coal (anthracite, bituminous, lignite), the location where it was mined, and the operating conditions of a plant. Flue gas desulferizer compounds consist of a number of products, the most prominent of which is gypsum.

About 47 percent of the combustion products generated annually in the United States are reused for a variety of purposes (American Coal Ash Association, 2014). Fly ash and bottom ash are used as additives for Portland cement, road and soil stabilizers, and bricks. Boiler slag is used for sandblasting and for traction control on ice- and snow-covered roads. Gypsum derived from FGD compounds can be used in wallboard. The remaining 53 percent of combustion products are placed in landfills or stored in water-filled impoundments near power plants. The U.S. Environmental Protection Agency recently issued new rules to promote the safe reuse, disposal, and storage of coal combustion products (U.S. Environmental Protection Agency, 2014a). The rules were developed in the wake of the 2008 spill of coal ash from an impoundment at a power plant in Kingston, Tennessee, that contaminated the Clinch and Emory Rivers (Ruhl and others, 2010). Cleanup costs for that spill exceeded 2 billion dollars.

Natural Gas

Natural gas is referred to as a clean fuel in terms of the relatively low toxicity of its byproducts. Carbon dioxide is emitted when gas is burned, but the amount emitted is about half that from coal (see Box J—Energy, Atmospheric Emissions, and Water Quality). Natural gas, as it comes out of the well, can contain water, oil, gas condensates, hydrogen sulfide, mercury, and other potential contaminants, many of which have economic value. The gas is processed to remove these constituents prior to use. Nitrogen oxides can form from gas combustion, but again, emission rates are substantially less than those for coal (see Box J—Energy, Atmospheric Emissions, and Water Quality). There is no significant combustion residue to deal with.

Nuclear

Water is essential for safe operation of today's nuclear power plants. The legacies of environmental damage and water pollution left by disasters at Chernobyl, Ukraine (1986), and Fukushima, Japan (2011), where cooling water could not be adequately supplied and reactor cores melted, will last decades or more (Alley and Alley, 2013). However, nuclear power plants have the environmental benefit of emitting no greenhouse gases.

Leaks from reactor piping can contribute to contamination of cooling water. The Nuclear Regulatory Commission allows power plants to release radioactive constituents to the environment under normal operating conditions if the radioactivity is below permissible levels. Details of all such releases are available to the public through the Nuclear Regulatory Commission's Agencywide Documents Access and Management System (ADAMS, *http://www.nrc.gov/reading-rm/adams.html*).

Spent fuel is also a potential source of water contamination; used fuel rods are stored in water baths to prevent them from overheating. Long-term disposition of spent nuclear fuel remains an unknown proposition in the United States. As of 2014, a permanent repository for the used fuel has not been selected. Many criteria are involved in making decisions on locations for such a repository, but the most important one is isolation of the fuel rods from water and the biosphere for many thousands or even hundreds of thousands of years. The suitability of Yucca Mountain, located in the Mojave Desert in Nevada, as a permanent repository was studied for more than 20 years by the U.S. Department of Energy, but the site was removed from consideration in 2009, prior to completion of the study (Alley and Alley, 2013).

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J Energy, Atmospheric Emissions, and Water Quality

The burning of fuels to generate electricity, power motor vehicles, heat buildings, and power industry leads to the emission of volatile and particulate combustion products into the atmosphere. The types and amounts of emissions depend on the fuel (table J–1) and the design and operation of the combustion vessel. In terms of total mass, carbon dioxide is the largest pollutant. Other important pollutants include sulfur dioxide, nitrogen oxides, and mercury. Atmospheric emissions are tied to water quality in a number ways, including global climate, acid deposition, and the transport of mercury and other trace elements.

Greenhouse gases, when present in the atmosphere, have the effect of increasing global temperatures. Carbon dioxide is the most prominent greenhouse gas (fig. J–1); other important greenhouse gases include methane, nitrous oxide, and fluorinated gases such as sulfur hexafluoride. The effect of a greenhouse gas on global climate depends on its atmospheric concentration, its heat absorbing capability (usually expressed in units of carbon dioxide equivalent), and the rate at which the compound decays or is removed from the atmosphere. Atmospheric concentrations of carbon dioxide have been increasing since the first measurements were made at Mauna Loa, Hawaii (fig. J–2) in the late 1950s. The increased concentrations are attributed to human activity, in particular energy consumption; combustion of fossil fuels accounted for 94 percent of total carbon dioxide emissions in the United States in 2011 (U.S. Environmental Protection Agency, 2013b). Energy operations in general, including release of methane from natural gas and oil wells, accounted for 86 percent of total greenhouse gas emissions in 2011 (U.S. Environmental Protection Agency, 2013b). Climate change affects many aspects of water availability and quality, including changes in precipitation and evapotranspiration patterns, possibly more intense storms, altered ecosystems, and sea-level rise. For a more in-depth discussion of climate change and its effects on water and energy resources, see the section "Science for Addressing the Water-Energy Nexus."

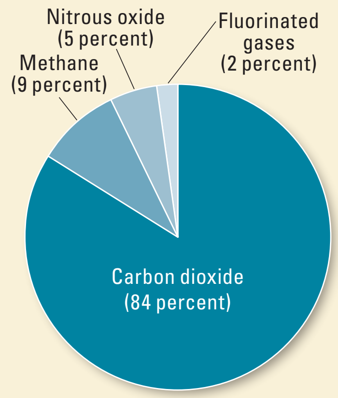


Figure J–1. Relative contributions to the total greenhouse gas emissions for the United States, 2011, as a percentage of the total emissions of 6.7 billion metric tons of carbon dioxide equivalent. (U.S. Environmental Protection Agency, 2013b)

Acid deposition (sometimes referred to as acid rain) is precipitation or dry atmospheric fallout that is acidic in nature; that is, it has a high concentration of hydrogen ions and a low pH value (U.S. Geological Survey, 2014a). Acid deposition can lead to the acidification of lakes and streams and can have deleterious effects on ecosystems, such as fish kills. Acid deposition occurs when sulfur dioxide and nitrogen oxides in the atmosphere are converted to sulfuric and nitric acid, respectively. Sulfur dioxide and nitrogen oxides are emitted naturally to the atmosphere by volcanic activity, but human activity, especially the combustion of coal, gasoline, and other fossil fuels (table J–1), is the primary source of atmospheric stores of these compounds. Laws and rules enacted over the past few decades for controlling emissions of these compounds (such as requirements for catalytic converters in motor vehicles and flue-gas desulfurization systems in power plant smokestacks) have resulted in a substantial decrease in acid deposition in the United States since 1985 (fig. J–3).

Table J–1. Gaseous and particulate emissions from the uncontrolled combustion of common fossil fuels. Hard coal refers to bituminous and subbituminous coal.

[Values are in grams per kilowatthour of thermal energy. NO_x, nitrogen oxides; <, less than]

Pollutant	Hard coal	Lignite	Fuel oil	Wood	Natural gas
Carbon dioxide	[1]340	[1]364	[1]279	[2]302	[1]202
Sulfur dioxide	[1]2.75	[1]4.90	[1]4.86	[2]0.04	[1]<0.0
NO_x	[1]1.05	[1]0.66	[1]0.70	[2]0.76	[1]0.34
Carbon monoxide	[1]0.32	[1]0.32	[1]0.06	[2]0.93	[1]0.05
Particulate matter	[1]4.33	[1]11.7	[1]0.06	[2]0.62	[1]<0.01
Mercury	[2]5.0×10^{-6}	[2]1.0×10^{-5}	[2]1.1×10^{-6}	[2]5.4×10^{-6}	([3])

[1]European Environmental Agency (2008).

[2]U.S. Environmental Protection Agency (variously dated).

[3]Mercury is removed from natural gas during processing.

The combustion of fossil fuels, primarily coal, for the generation of electricity accounts for close to 70 percent of all atmospheric mercury produced by humans in the United States (Engle, 2005). Atmospheric mercury follows a complex pathway of possible reactions including deposition, re-emission, oxidation, reduction, methylation, and bioaccumulation. Elemental mercury, the dominant form of atmospheric mercury, has only limited solubility and

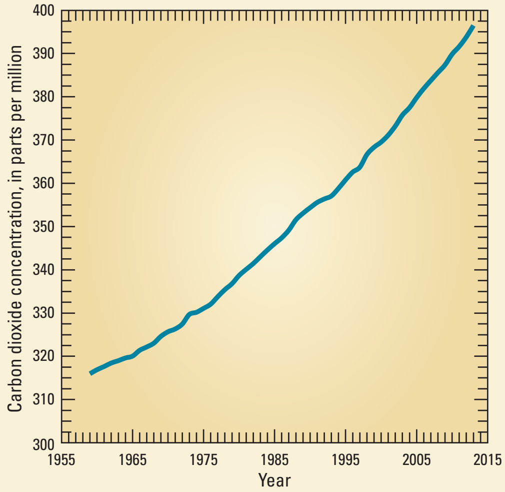


Figure J–2. Mean annual atmospheric carbon dioxide concentrations as measured at Mauna Loa, Hawaii, 1959–2013. (National Oceanic and Atmospheric Administration, 2013)

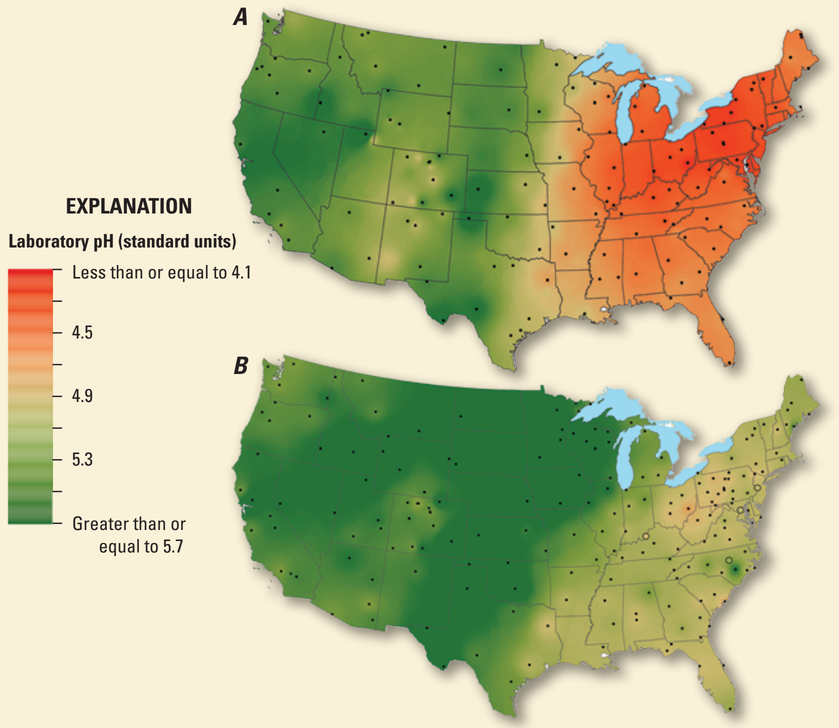


Figure J–3. Average annual pH values in precipitation for (*A*) 1985 and (*B*) 2012 indicate a substantial reduction in acid deposition over this period. (National Atmospheric Deposition Program, 2014)

reactivity, allowing for long travel distances before it reenters the surface environment (fig. J–4). Mercury causes problems in many ecosystems. For example, fish and other aquatic biota can bioaccumulate organic forms of mercury (derived from the methylation of elemental mercury), rendering them unfit for human consumption. Fish advisories in many parts of the United States have been linked to atmospheric deposition of mercury (Cocca, 2001). The emission of mercury from power plants can be controlled though a variety of technologies. In a typical plant burning bituminous coal in conjunction with fabric filters and flue-gas desulfurization systems, roughly 60 percent of the original mercury is removed, and the remaining 40 percent is emitted to the atmosphere (Kolker and others, 2006). Despite available technology, approximately 40 percent of the roughly 1,400 coal and oil-fired generating units in the United States do not use advanced pollution controls (U.S. Environmental Protection Agency, 2013b).

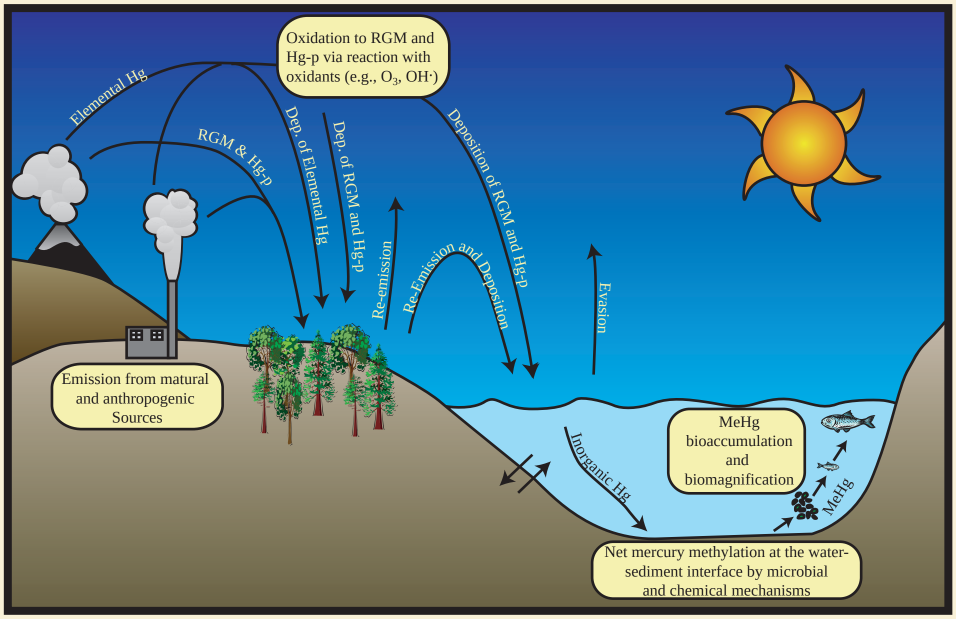


Figure J–4. Environmental pathways for mercury (Hg) emitted to the atmosphere and potential for uptake and bioaccumulation in aquatic organisms. (RGM, reactive gaseous mercury; Hg-p, particulate bound mercury; MeHg, methylmercury; O_3, ozone; and OH-, hydroxyl radical) (From Engle, 2005)

K Carbon Capture and Sequestration

To limit carbon emissions and climate change, carbon dioxide (CO_2) can be captured from large stationary sources, such as coal-fired power plants, compressed to a liquid state, and injected deep underground into permeable geologic strata (Duncan and Morrissey, 2011). Potential storage formations include deep saline formations, depleted oil and gas reservoirs, and coal seams that are not considered economically viable for mining. The technology for sequestering CO_2 is still being developed. On a smaller scale, CO_2 has been injected into geologic formations for many decades as part of enhanced oil recovery efforts in the United States, but as of 2014, the United States had no commercial geologic carbon sequestration systems in operation. Two sequestration systems, however, are operational in Norway, as well as one in Algeria (Global CCS Institute, 2013). These systems do not involve CO_2 capture at power plants. Instead, the injected CO_2 is an unwanted byproduct of natural gas extraction.

Geologic carbon sequestration faces many challenges. To be viable as a strategy for reducing greenhouse gases, vast amounts of carbon dioxide would need to be stored in geologic formations. The geologic formations into which the fluid is injected must be sufficiently porous and permeable and must be overlain by layers of impermeable rock to store and isolate the CO_2 for long periods of time. A key challenge for carbon sequestration is to avoid affecting current or future underground sources of drinking water. One potential adverse effect of sequestration is the displacement of saline water into freshwater-bearing horizons; another is the escape of carbon dioxide to shallower water horizons, which could cause acidification of groundwater and mobilization of trace elements. Improperly abandoned or damaged oil and gas wells are an important concern because they can provide short circuits back to the biosphere.

Carbon capture will lead to increased water withdrawal and consumption rates at coal- and natural gas–fueled thermoelectric power plants. Additional water requirements are associated with capture and compression of CO_2. In addition, carbon capture systems reduce power-plant thermal efficiency, so more water will be required for cooling and fuel processing.

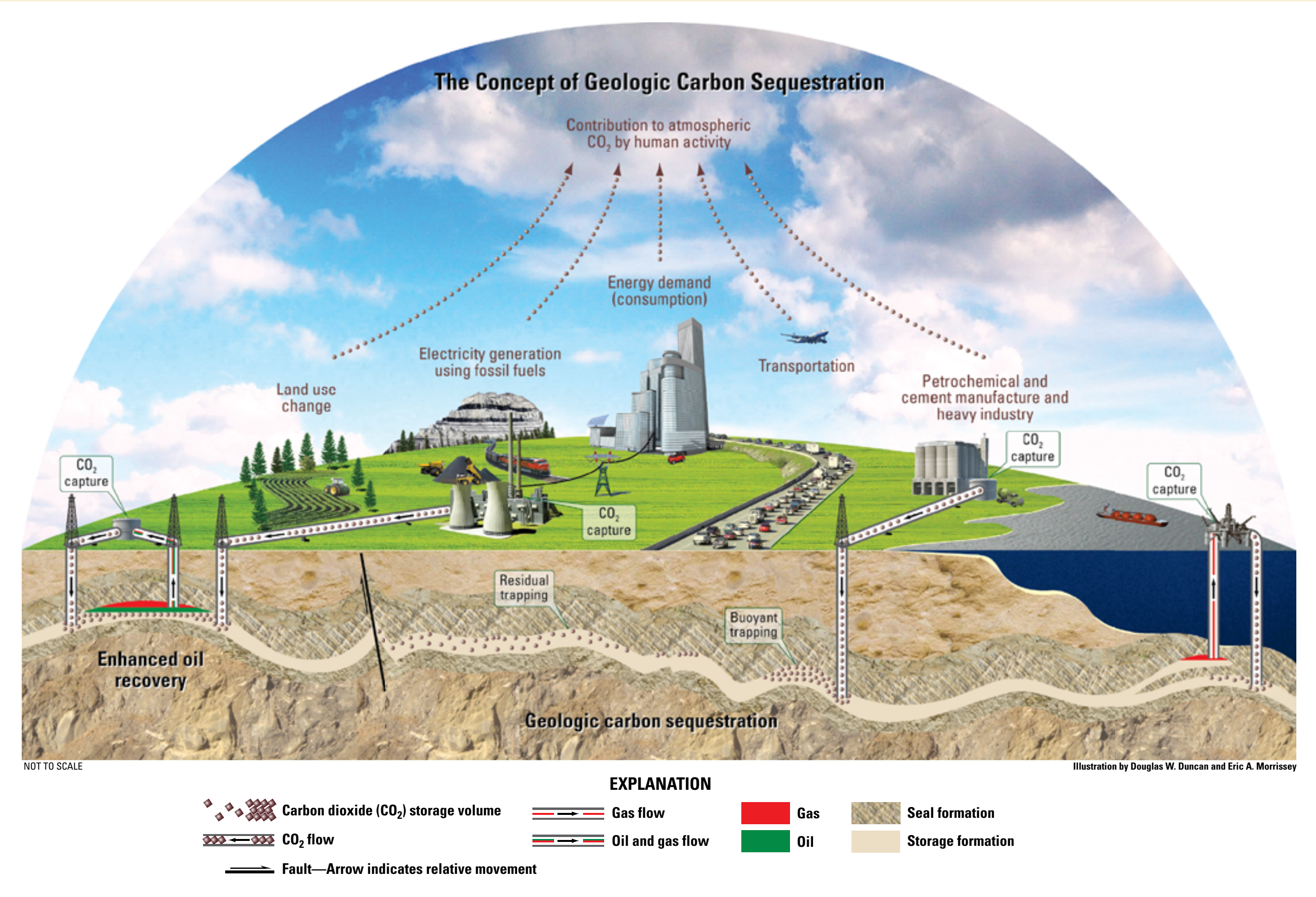


Figure K–1. The concept of geologic carbon sequestration. (From Duncan and Morrissey, 2011)

The exact amount of additional water required is not known. Estimates of increased withdrawal and consumption rates are as high as 90 and 75 percent, respectively (Meldrum and others, 2013). Ongoing research and development by the U.S. Department of Energy and others is seeking ways to reduce this water consumption penalty.

Identifying potential geologic storage formations and determining the amount of CO_2 that can be sequestered on a national basis are important for long-term planning. The U.S. Geological Survey recently completed an evaluation of the technically accessible storage resource for CO_2 for 36 sedimentary basins in the onshore areas and State waters of the United States (U.S. Geological Survey, 2013). The estimated mean storage capacity was approximately 3,000 metric gigatons of CO_2, roughly 500 times the 2011 annual energy-related CO_2 emissions for the United States (U.S. Geological Survey, 2013). The estimate was determined by using a probabilistic approach based on current geologic and hydrologic knowledge of the subsurface and current engineering practices. As illustrated in figure K–1, CO_2 storage occurs by two mechanisms—buoyant trapping and residual trapping. In buoyant trapping, the formation pore space is filled with CO_2 and is held in place by seal formations on the top and sides of the porous rock. Buoyant trapping is analogous to the mechanism by which oil and gas are naturally trapped in conventional subsurface reservoirs and is illustrated in the figure by the accumulation of CO_2 in arc-shaped structures (anticlines) that are overlain by low-permeability seal formations. Residual trapping occurs as injected CO_2 passes through the storage formation and leaves some CO_2 behind; the CO_2 is held in place by surface tension in pore spaces. Residual trapping accounts for 98 percent of the estimated CO_2 storage capacity; however, depleted conventional oil and gas reservoirs with large capacities for buoyant trapping might be favored locations for CO_2 storage because of the accrued knowledge of these systems (U.S. Geological Survey, 2013).

Long-term success of any geologic carbon sequestration or wastewater injection operation also depends on a full understanding of the physical and chemical interactions among injected fluids, formation groundwater, and formation minerals (Kharaka and others, 2009). Processes such as dissolution and precipitation can alter rock porosity, thereby changing the amount of available storage space. Injection pressures that are too great can induce seismic activity or possibly fracture rocks and create unintended pathways for fluid migration (see Box H—Subsurface Fluid Injection).

View to the south of Yucca Mountain crest. Yucca Mountain was once considered as a repository for high-level nuclear waste.

Biomass

Biomass power plants have become popular since 2000 as green alternatives to fossil fuel–based power plants. Combustion of biomass, however, as with fossil fuels, is accompanied by the release of particulates and gases, including carbon dioxide, nitrogen oxides, volatile organic compounds, and sulfur compounds, into the atmosphere (table J–1). Biomass combustion can be viewed as being carbon neutral because the organic matter would eventually decompose and emit the same amount of carbon, but because coal-fired power plants are more efficient than biomass plants (table 3), carbon dioxide emissions for wood are about 30 percent more than those for coal per kilowatthour of generated electricity.

Ethanol plant in South Dakota.

Hydroelectric Power Plants

Hydroelectric power refers to electricity produced from the gravitational force of falling water. Hydroelectric plants produced approximately 269 billion kWh of electricity in the United States in 2013, representing about 7 percent of total electricity generated in the country (U.S. Energy Information Administration, 2014b). Hydroelectric power is more important on a global scale, accounting for approximately 19 percent of electrical power worldwide.

The water intensity of hydroelectricity is more problematic to estimate than that of electricity generated at thermoelectric power plants. Water consumption for generation of hydroelectricity consists of evaporation that occurs from reservoirs that feed hydroelectric plants. Hence, calculations of water intensities require estimates of evaporation rates. In addition, many dams are constructed for multiple purposes, such as municipal, agricultural, and industrial water supply; navigation; flood control; and recreation; as well as generation of hydroelectricity. No commonly accepted methodology exists for determining how much reservoir evaporation should be attributed to hydroelectricity, or other specific reservoir uses (Bakken and others, 2013). If a dam were constructed specifically for the generation of hydroelectricity, it may be appropriate to attribute all of the evaporative loss from a reservoir to generation of electricity. Many dams in the western United States were constructed specifically for irrigation water supply, with hydroelectric plants installed many years later; evaporation from these reservoirs is perhaps best assigned entirely to irrigation.

Reservoir water consumption rates can be expressed as

$$Q_{op} = (ET_0 - ET)*A \qquad (1)$$

where

Q_{op} is annual operational consumption of water, in cubic meters per year;

ET_0 is the evaporation rate of open water, in meters per year;

ET is the estimated evapotranspiration rate of the impounded area prior to being inundated; in meters per year; and

A is the surface area of the reservoir, in square meters.

Evapotranspiration refers to the combined evaporation from open water surfaces, soil, and plants. Equation 1 does not account for water moving from the reservoir to the underlying groundwater system; this water is not considered consumed water because it is theoretically still available for use.

Evaporation and evapotranspiration rates depend on weather patterns, air temperatures, and solar radiation. Evapotranspiration rates also depend on vegetation and available soil-water content; if the supply of soil water is unlimited, as occurs in many humid regions, then ET values should be very similar to those of ET_0. In arid regions, ET is substantially less than ET_0. Because hydroelectric plants are located in all parts of the country, water consumption rates for generation of hydroelectricity vary across the United States. There is no nationwide network for monitoring reservoir evaporation; however, consumption rates for hydroelectric plants located in humid settings should be less, in general, than those for plants located in arid regions, assuming similar dam and reservoir characteristics.

Construction of Hoover Dam between 1933 and 1935 used 3.33 million m^3 of concrete, requiring about 2 billion L of water. Although this is a substantial quantity of water, it is equivalent to less than 1 percent of the amount of water that evaporates from Lake Mead each year (Moreo and Swancar, 2013).

As an example, we calculate the water intensity for a hydroelectric system in the northern Cascade Mountains of Washington. The Skagit River Hydroelectric Project was built to supply electricity to the city of Seattle. The project contains three dams that generate about 2.1 billion kWh/yr. The three reservoirs in the project have a combined surface area of about 52 km^2 and are located in a humid region with annual precipitation of about 1.468 m and annual ET_0 of about 0.648 m (calculated from average pan evaporation of two nearby National Weather Service sites). Application of equation 1 with ET assumed to be 0.508 m/yr (Drost and Lombard, 1978) indicates that annual water consumption for the three reservoirs is about 7.3 billion liters. Because this project was constructed specifically for hydroelectricity generation, it is reasonable to assign all water consumption to that purpose. Thus, the water intensity for hydroelectricity from the Skagit River Hydroelectric Project is calculated to be about 3.5 L/kWh, a value somewhat greater than water intensities for most other forms of electricity generation (table 3).

The design of the Skagit River Hydroelectric Project and its location in a humid setting, where the reservoir water-consumption rates are relatively low, imply that the calculated water intensity of 3.5 L/kWh is less than that of most other large hydroelectric plants in the United States, at least those plants associated with reservoir-dam systems designed exclusively for the generation of hydroelectricity. We do not attempt to estimate a maximum water intensity for hydroelectricity because of the complexities involved and lack of available data. The average water intensity for hydroelectricity in the United States was estimated to be 69 L/kWh of electricity by Torcellini and others (2003). That estimate is unrealistically high because the study assigned all reservoir evaporation to the generation of hydroelectricity and invoked a uniform assumption that *ET* in equation 1 was equal to 0. If that value of 69 L/kWh were correct, then the amount of water consumed for the generation of hydroelectricity would substantially exceed the total combined water consumption for all other forms of electricity generation in the United States on an annual basis. Accurate determination of average water intensity for hydroelectricity in the United States cannot be made until a standardized methodology is developed for apportioning reservoir evaporation among various reservoir uses.

Pumped-storage hydroelectric systems provide a unique and important form of energy storage in some parts of the United States. The systems consist of reservoirs above and below a traditional dam and a series of pumps that can transport water from the lower to the upper reservoir. These systems operate at a net energy loss (about 20 to 40 percent more energy is required to pump the water up than is obtained from water flowing through the dam), but they help to balance daily variations in energy loads. Demands for electricity fluctuate throughout the day, with the highest demands during daylight hours and the lowest demands at night. The strategy for pumped systems is to pump water to the upper reservoir during the nighttime when electricity demand and price are low; the water can then be released to pass through the hydroelectric plant during peak-demand times. Pumped storage is the largest energy storage system within the U.S. power grid; electrical generating capacity was about 21 GW in 2013 (National Hydropower Association, 2013).

Hydroelectric plants have several beneficial features: no fuel is required, very little in the way of greenhouse gases or other waste products is generated, and power can be quickly ramped up or down to meet ever changing energy demands. Dams change the natural course of rivers, however, and can have adverse effects on aquatic ecosystems (Collier and others, 1996), such as disruption of natural aquatic habitats, elimination of sediment flows below dams, entrainment and impingement of fish and other aquatic life in turbines, and alteration of natural temperature and oxygen levels in streams. As an example, dams that were built in past decades on the Columbia River in Washington have cut off salmon and other fish from more than 1,700 km of natural spawning habitat (Northwest Power and Conservation Council, 2010). Dam construction in the United States has slowed considerably in recent years, largely because of concerns for ecosystems. However, hydroelectric generating capacity continues to expand with addition of generators to existing non-powered dams and conduits.

Wind and Passive Solar

Water requirements for wind and passive solar energy development are generally low. Relatively small amounts of water may be needed for construction and installation of wind turbines, and the construction of solar panels consumes the equivalent of about 0.3 L/kWh (Meldrum and others, 2013). Once wind turbines and solar panels begin generating electricity, the only water-related issue is the need for water to periodically clean turbine blades and solar panels.

Summary Water Requirements—Electricity and End-Use Sectors

Energy use can be partitioned into electrical power generation and four end-use sectors: transportation, industrial, residential, and commercial (fig. 19). Electricity generation accounts for about 40 percent of all energy consumption in the United States, more energy than is used directly in any individual end-use sector. Electricity is an intermediate form of energy, and the energy consumed in generating it can be apportioned to the end-use sectors on the basis of electricity use. For each sector, primary and total energy consumption can be determined. Primary consumption (fig. 19) is the direct use of an energy source, such as the use of natural gas to heat homes or the use of gasoline to power cars. Total energy consumption (fig. 20) includes primary energy consumption and the energy required to provide the electricity that is used by each sector. In the discussions that follow, energy consumption for the use sectors is provided in terms of both primary and total consumption.

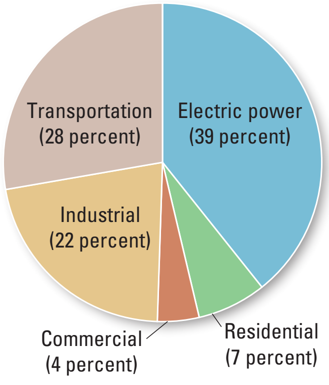


Figure 19. Primary energy consumption in the United States for electricity generation and four end-use sectors, 2013, as a percentage of the total consumption of 28.5 trillion kilowatthours of thermal energy. (U.S. Energy Information Administration, 2014b.)

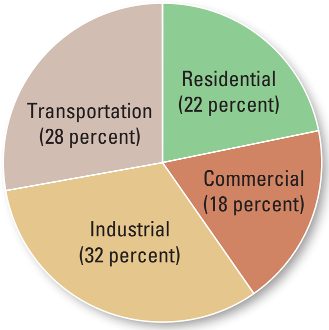


Figure 20. Total energy consumption for the United States by end-use sector, 2013, as a percentage of the total consumption of 28.5 trillion kilowatthours of thermal energy. (U.S. Energy Information Administration, 2014b.)

Direct use of energy often involves little in terms of water requirements. Flipping the switch of a house light, adjusting a room thermostat, and driving a car to work are actions that outwardly require no direct water use; however, as shown in the preceding sections, water is consumed by almost all stages of delivering that electricity to the house or that gasoline to the filling station. The end-use sectors provide a convenient framework for analyzing the amount of water consumed for energy-related functions.

Total water consumption for each end-use sector is determined by summing the requirements for each phase of energy production and use including fuel extraction or growth, fuel processing and transportation, generation of electricity, and end use. As with energy consumption, water consumption for electricity generation can be assigned to specific end-use sectors. A general lack of site-specific data and the large variability in processing techniques make it difficult to accurately quantify all energy-related water consumption on a national scale, but water consumption for the different end-use sectors can be discussed in terms of ranges of estimated values.

Water-quality issues associated with energy production and use are more difficult to summarize than water consumption. Unlike water consumption, the water-quality issues addressed in previous sections cannot simply be added up on a use-sector basis. Water-quality issues related to the generation of electricity were addressed in the previous section, and, in general, the end use of electricity does not introduce additional issues. Water-quality issues associated with primary energy consumption in the transportation, residential, and commercial use sectors are related to possible leaks during transport and storage of fuels and atmospheric emissions of carbon dioxide and other pollutants (see Box J—Energy, Atmospheric Emissions, and Water Quality). Water-quality issues associated with the industrial-sector energy use cannot be fully assessed because of the general lack of information on processes in this sector and because not all water used in this sector is tied to energy.

Electricity

The total water intensity of producing one kilowatthour of electricity is calculated by adding the water intensity for extracting and processing the fuel that is used in generating that electricity and the water intensity of the electrical power plant. Water consumption rates for extraction and processing of fuel were previously given in terms of water volume per unit mass or volume of fuel (table 1). These rates can be converted to water intensities in units of liters of water per equivalent kilowatthour of electricity by accounting for fuel energy content and power-plant thermal efficiency. Total water intensities for the generation of electricity by different fuels and types of power plants and cooling systems are presented in table 4, which combines the water intensities of power plants (table 3) with those for extraction and processing (table 1). Figure 21 shows the range of the total annual water consumption for electricity generation in the United States for 2013 estimated on the basis of the given water intensities.

Total water intensity for producing electricity by steam turbine appears to be slightly less for coal-fired power plants than for nuclear and natural gas–fired power plants with identical cooling systems (table 4). Combined-cycle natural gas power plants are less water intensive than gas steam plants. Generation of electricity at hydroelectric, geothermal, or concentrating solar power plants (all renewable sources) is more water intensive than generation of electricity at fossil-fuel power plants. Wind and passive solar power plants have essentially negligible water intensities.

Estimates of annual water consumption for all electricity generation in the United States in 2013 range from 4.1 to 9.5 trillion L/yr (table 4, fig. 21). These estimates are derived from data in published reports. The broad range illustrates the large uncertainty inherent in determining a nationwide consumption rate. Thermoelectric power plants account for most of the water consumed in the generation of electricity. Diehl and Harris (2014) provide a detailed analysis of water withdrawal and consumption rates at 1,290 individual power plants in the United States. The cumulative consumption for those plants in 2010 was about 4.8 trillion L (Diehl and Harris, 2014); those authors caution that any estimate of water consumption at the national scale could be in error by 20 percent or more. The estimated consumption rate for the generation of hydroelectricity (900 billion L/yr) should be considered a minimum value because of difficulties previously described. The uncertainty in consumption estimates reflects a lack of site-specific data as well as limitations of estimation methods. This uncertainty clouds our current understanding of water use at power plants and complicates efforts to predict future water needs for generating electricity.

Water consumption for generation of electricity is just a fraction of the 222 trillion L that were withdrawn by thermoelectric power plants in 2010. The range in total water consumption given in table 4 is equivalent to 2 to 4 percent of water withdrawn by power plants in 2010. Per capita electrical use in the United States was approximately 12,400 kWh for 2013, equivalent, in terms of thermal energy, to about 36,000 kWh_{th}. Associated annual water consumption for generation of electricity was in the range of 13,000 to 30,000 L per capita.

The U.S. Energy Information Administration allocates electricity use to the four end-use sectors on the basis of sales. For 2013, residential customers used 38 percent of generated electricity, commercial customers used 36 percent, industry accounted for 26 percent, and transportation used a negligible amount (0.2 percent) (U.S. Energy Information Administration, 2014b). Water consumption for electricity can likewise be allocated to specific end-use sectors, and total energy-related water consumption can be tallied for each sector.

Table 4. Estimates of water consumption in the United States for different types of electricity generation in terms of water intensity (in liters of water per kilowatthour of generated electricity) and in terms of total water consumed in 2013.

[L/kWh, liters of water per kilowatthour of electricity; yr, year; na, not applicable; ~, approximately]

Plant type	Cooling process	Water consumption rate for fuel extraction/processing (L/kWh)	Power plant water consumption rate[1] (L/kWh)	Total water consumption rate (L/kWh)	Annual electricity generated[2] (trillion kWh/yr)	Annual water consumption (trillion L/yr)
Coal	Once-through	[3]0.03–0.19	0.2–1.2	0.2–1.4	1.57	[7]1.5–3.3
	Tower	[3]0.03–0.19	1.6–2.5	1.6–2.7		
Nuclear	Once-through	[4]0.05–1.2	0.4–1.5	0.5–2.7	0.79	[7]1.1–2.8
	Tower	[4]0.05–1.2	2.2–3.4	2.3–4.6		
Natural gas steam	Once-through	[3]0.09–1.2	0.7–1.7	0.8–2.9	1.01	[8]0.4–2.2
	Tower	[3]0.09–1.2	2.1–4.2	2.2–5.4		
Natural gas combined cycle	Once-through	[3]0.07–0.9	0.1–0.9	0.2–1.8		
	Tower	[3]0.07–0.9	0.2–1.1	0.3–2.0		
Biomass	Tower	~0	1.8–3.6	1.8–3.6	0.03	0.1
Geothermal steam (binary)	Tower	na	6.8–9.9	6.8–9.9	0.02	0.1–0.2
Concentrating solar (parabolic trough)	Tower	[5]0.6	2.1–7.2	2.7–7.8	0	0
	Dry	[5]0.6	[4]0.1–0.5	0.7–1.1		
Hydroelectric[6]	na	na	3.5	3.5	0.27	0.9
Wind	na	na	~0	~0	0.17	0
Total	na	na	na	na	3.90	4.1–9.5

[1]From table 3.

[2]U.S. Energy Information Administration (2014a).

[3]From table 1.

[4]Meldrum and others (2013).

[5]For plant construction (Meldrum and others, 2013).

[6]Value for hydroelectric power is for reservoir evaporation from example in this report. It should be considered a minimum value. As described in the text, average and maximum water intensities for generation of hydroelectricity cannot be determined because of a lack of standardized methodology and data.

[7]Assumes percentages of once-through and tower cooling from Diehl and Harris (2014).

[8]Includes both natural gas steam and combined cycle; assumes percentages of once-through and tower cooling from Diehl and Harris (2014).

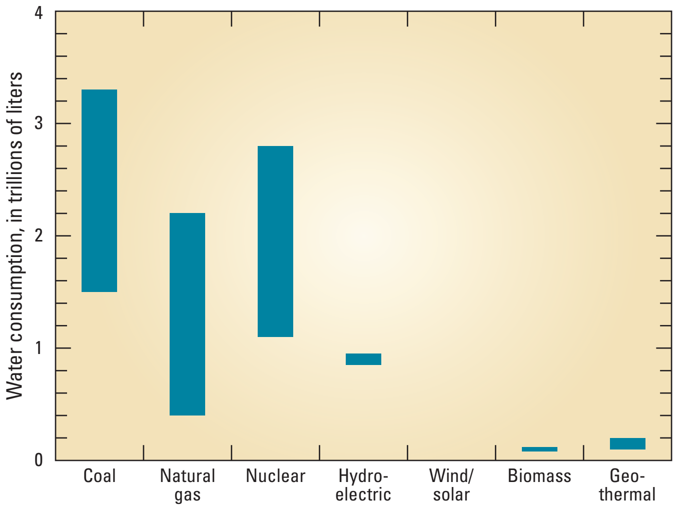


Figure 21. Estimated range of water consumption for the generation of electricity in the United States by method of generation, 2013. The estimated consumption rate for generation of hydroelectricity (900 billion liters per year) should be considered a minimum value. As described in the text, average and maximum consumption rates for generation of hydroelectricity cannot be estimated because of a lack of standardized methodology and data.

Transportation

Transportation of people and commodities by car, truck, bus, boat, train, and airplane accounted for 28 percent of all energy consumption in the United States in 2013. Oil products represent about 93 percent of all transportation fuels, and biofuels account for a relatively small proportion of transportation fuels (about 4.5 percent). Water requirements for production and refinement of these fuels, as described previously, are summarized in table 5 and figure 22.

The large contribution of irrigated biofuel crops to overall water consumption in the transportation sector is noteworthy. The estimated range of water consumption for all transportation fuels is 6.5 to 9.1 trillion L/yr. Biofuels may account for 38 to 54 percent of that consumption, even though biofuels are just a small fraction of all transportation fuels. Irrigation of corn and soybean crops results in high water consumption rates for the production of bioethanol and biodiesel relative to the production of hydrocarbon fuels. Bioethanol and biodiesel also have less energy content than gasoline and diesel fuel (table 2). Flexible fuel vehicles operating on E85 typically see a drop in fuel economy (kilometers per liter) of 25 to 30 percent relative to that of gasoline (U.S. Department of Energy, 2012). Therefore, when water intensity is determined on a fuel-economy basis, biofuels consume even more water.

On a per capita basis, Americans consume about 2,800 L of gasoline or other transportation fuels each year, equivalent, in terms of thermal energy, to about 25,000 kWh_{th} (U.S. Energy Information Administration, 2014b). Estimated annual water consumption for transportation fuels in the United States is between 20,000 to 29,000 L per person, equivalent to about 55 to 79 L of water per day. If only hydrocarbon-based fuels were used for transportation, the associated range of per capita water consumption would shrink to about 9,000 to 17,000 L/yr (25 to 45 L/d).

Table 5. Estimates of water consumption in the United States for different types of transportation fuels in terms of rates of consumption (in liters of water per liter of fuel) and in terms of total water consumed in 2013.

[Water consumption rates for natural gas are given in L/kWh_{th}. L, liter; kWh_{th}, kilowatthours of thermal energy; --, unknown; na, not applicable]

Fuel type	Water consumption for fuel production or growth (L/L)	Refinery water consumption (L/L)	Total water consumption (L/L)	Percentage of total transportation fuels[1]	Annual energy consumed for transportation in 2013[1] (trillion kWh_{th})	Annual water consumed for transportation fuels in 2013 (trillion L)
Oil products	[2]2.1–5.1	[2]1.5	3.6–6.6	92.5	7.31	3.0–5.5
Bioethanol	[3]56	[3]2.3	58.3	3.9	0.31	3.2
Biodiesel	[4]57	[4]1–3	58–60	0.6	0.05	0.3
Natural gas	--	--	[5]0.03–0.4 L/kWh_{th}	2.9	0.23	0–0.1
Gasoline from oil sands	[6]0.4–5.8	[2]1.5	1.9–7.3	0	0	0
Gasoline from oil shale	[7]0.8–11.1	[1]1.5	2.3–12.6	0	0	0
Gasoline from coal	--	--	[8]5–7.3	0	0	0
Total	na	na	na	100	7.90	6.5–9.1

[1]U.S. Energy Information Administration (2014a).

[2]Wu and others (2009), and Wu and Chiu (2011).

[3]This report and Mueller (2010).

[4]This report, Pate and others (2007), and National Research Council (2008).

[5]From tables 2 and 4.

[6]Moorhouse and others (2010).

[7]Government Accountability Office (2010).

[8]U.S. Department of Energy (2006).

Biofuels make up about 5 percent of transportation fuels in the United States, but they may account for more than 50 percent of all water consumed for transportation fuels.

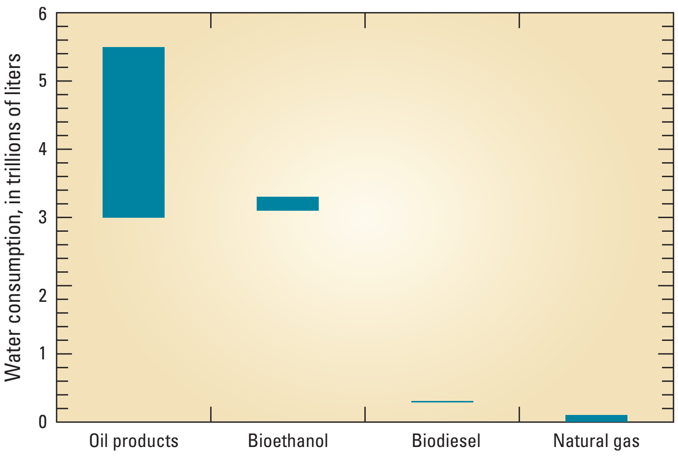


Figure 22. Estimated water consumption for the production of transportation fuels in the United States, 2013.

Industrial

The industrial sector, comprising petroleum, chemical, paper, food, mineral, mining, and other industries, accounted for about 32 percent of total energy consumption in the United States in 2013 (U.S. Energy Information Administration, 2014b). A mix of fuels is used at industrial facilities: natural gas and oil products each account for about 40 percent of primary energy consumption, renewable sources account for about 11 percent, and coal accounts for the remaining 9 percent of consumption. Not all of these fuels are combusted to provide energy. Oil and natural-gas products are essential ingredients in many petrochemicals, agricultural chemicals, and other useful products. The fuel added to these products represented about 32 percent of the direct energy resources attributed to this sector in 2010 according to a survey by the U.S. Energy Information Administration (2010). The remaining 68 percent of the energy resources were used as fuel for chemical and mechanical processes, generation of electricity, and heating buildings.

Energy-related water needs for the industrial end-use sector are largely unknown. In addition, water is used in industrial operations that do not involve energy, such as washing, and it may not be possible to distinguish that water use from energy-related water use. As such, we are not able to provide exact details for energy-related water consumption for the industrial sector. We can, however, estimate the amount of water that would be needed if we ignore the 32 percent of fuels that are used as ingredients of other products and assume that the remaining 68 percent of energy resources are used to generate electricity at the water intensities shown in table 4 for natural gas. In this scenario, total annual water consumption for the primary consumption of energy is estimated to fall in the range of 0.9–4.8 trillion L, and total consumption (which includes electricity use) is estimated to fall in the range of 2.0–7.3 trillion L.

Residential and Commercial

The residential and commercial sectors use energy in similar ways. Primary energy consumption for both sectors goes mainly toward heating buildings and secondarily toward heating water. Natural gas is the most widely used fuel in homes and businesses, accounting for 75 percent of direct energy consumption for these sectors. Oil products (including natural-gas liquids) and wood account for most of the remaining primary energy consumption. The residential sector accounted for 7 percent of direct energy consumption and almost 38 percent of electricity use in 2013, whereas the commercial sector accounted for about 4 percent of direct energy consumption and about 36 percent of electricity use (U.S. Energy Information Administration, 2014b).

The energy consumed in generating the electricity for the residential and commercial sectors is much greater than the primary energy consumed in those sectors. Similarly, total energy-related water consumption for these sectors is dominated by the water needed to generate the electricity used in these sectors (tables 6 and 7). Water consumption for primary energy use is negligible, but water is needed for extracting and processing fuels that are used. Total energy-related consumption of water for the residential sector is estimated to be in the range of 1.7 to 4.4 trillion L for 2013 (fig. 23), equivalent to about 3 to 8 percent of water withdrawn nationwide in 2010 for public and domestic water supply (Maupin and others, 2014). Total energy-related water consumption for the commercial sector is estimated to be 1.6 to 3.9 trillion L for 2013 (fig. 24).

Primary energy consumption for the residential and commercial sectors in 2013 was about 10,000 kWh_{th} on a per capita basis; annual water consumption associated with the primary energy consumption falls in the range of 600 to 4,100 L per capita. Total energy consumption for these sectors for 2013, including the use of electricity, was about 36,000 kWh_{th} per capita, and the associated per capita water consumption is estimated to be in the range of 10,000 to 26,000 L.

Comparison of Water Consumption for Electricity and End-Use Sectors

So what do all these water-use numbers tell us? We, as Americans, consume a lot of energy. We also consume large amounts of water to produce that energy. A summary of estimated energy-related water consumption for 2013 is provided in table 8 and figure 25 for individual end-use sectors. Estimated total energy-related water consumption is in the range of 11.9 to 24.8 trillion L, equivalent to 2 to 5 percent of water withdrawn for all uses in 2010. The wide range in these estimates illustrates the high level of uncertainty inherent in the estimates. The uncertainty makes it impossible to precisely quantify water consumption rates.

Table 6. Estimates of energy and related water consumption for primary and total energy consumption for the residential end-use sector in the United States in 2013. Primary consumption is direct consumption of energy. Total consumption includes primary consumption and energy consumption required to generate the electricity used in each sector.

[Oil includes natural gas liquids. L, liter; kWh_{th}, kilowatthours of thermal energy; na, not applicable]

Fuel type	Water consumption rate for fuel production (L/kWh_{th})	Percent primary energy consumption for sector[1]	Primary energy consumption[1] (trillion kWh_{th})	Percent total energy consumption for sector	Annual water consumed for energy use (trillion L)
Natural gas	[2]0.03–0.4	74	1.48	24	0.0–0.6
Oil	[3]0.4–0.7	14	0.27	4	0.1–0.2
Biomass and other renewables	0	12	0.24	4	0
Primary energy/water use	na	100	1.99	32	0.1–0.8
Electricity	na	na	4.23	68	[4]1.6–3.6
Total	na	na	6.22	100	1.7–4.4

[1]U.S. Energy Information Administration (2014a).

[2]From table 5.

[3]From tables 2 and 5.

[4]From table 4.

Table 7. Estimates of energy and related water consumption for primary and total energy consumption for the commercial end-use sector in the United States in 2013. Primary consumption is direct consumption of energy. Total consumption includes primary consumption and energy consumption required to generate the electricity used in each sector.

[Oil includes natural gas liquids. L, liter; kWh_{th}, kilowatthours of thermal energy; na, not applicable]

Fuel type	Water consumption rate for fuel production (L/kWh_{th})	Percent primary energy consumption for sector[1]	Primary energy consumption[1] (trillion kWh_{th})	Percent total energy consumption for sector	Annual water consumed for energy use (trillion L)
Natural gas	[2]0.03–0.4	82	0.98	19	0.0–0.4
Oil	[3]0.4–0.7	14	0.17	3	0.1
Biomass and other renewables	0	3	0.04	1	0
Primary energy/water use	na	100	1.19	23	0.1–0.5
Electricity	na	na	4.06	77	[4]1.5–3.4
Total	na	na	5.25	100	1.6–3.9

[1]U.S. Energy Information Administration (2014a).

[2]From table 5.

[3]From tables 2 and 5.

[4]From table 4.

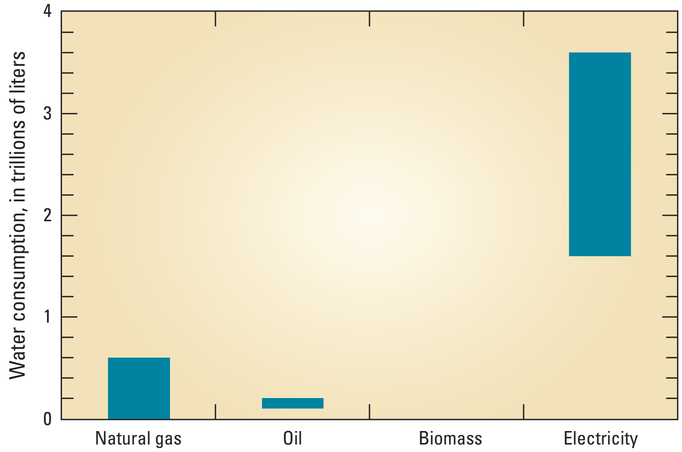


Figure 23. Estimated energy-related water consumption in the residential end-use sector of the United States by fuel, 2013. Oil includes natural-gas liquids.

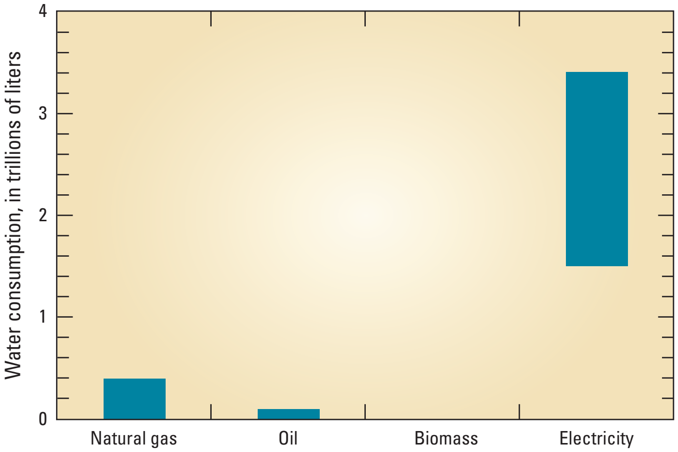


Figure 24. Estimated energy-related water consumption in the commercial end-use sector of the United States by fuel, 2013. Oil includes natural-gas liquids.

Electricity generation accounts for about 39 percent of all energy consumption in the United States. Electricity generation also consumes large volumes of water (table 4). Primary energy consumption for electricity generation and the transportation sector consumes similar quantities of water (tables 4 and 8). Less water is consumed for primary energy consumption in the industrial sector, and much less is consumed for primary energy consumption in the residential and commercial sectors (table 8). Although there is a large range in estimated water consumption rates associated with total energy consumption for each end-use sector, it appears that the transportation sector has the highest energy-related water consumption rates followed by the industrial sector and then the residential and commercial sectors.

A 110-kilovolt power line.

Table 8. Estimates of energy and energy-related water consumption in the United States in 2013, by end-use sector. Primary consumption is direct consumption of energy. Total consumption includes primary consumption and energy consumption required to generate the electricity used in each sector.

[L, liter; kWh_{th}, kilowatthours of thermal energy]

Sector	Primary energy consumption[1] (trillion kWh_{th})	Water associated with primary energy consumption (trillion L)	Total energy consumption[1] (trillion kWh_{th})	Water associated with total energy consumption[2] (trillion L)
Transportation	7.90	6.5–9.1	7.92	6.6–9.2
Industrial	6.20	0.9–4.8	9.10	2.0–7.3
Residential	1.99	0.1–0.8	6.22	1.7–4.4
Commercial	1.21	0.1–0.5	5.27	1.6–3.9
Total of end-use sectors	17.30	7.6–15.2	28.51	11.9–24.8

[1]U.S. Energy Information Administration (2014a).

[2]Water for electricity generation from table 4.

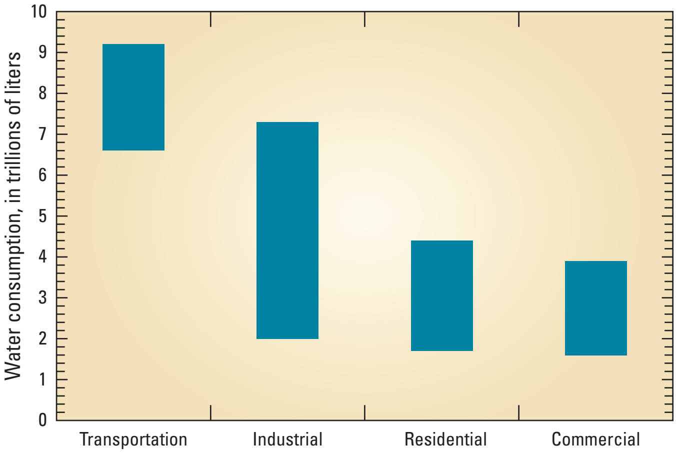


Figure 25. Estimates of total energy-related water consumption in the United States by end-use sector, 2013.

Energy for Water Development, Distribution, and Use

About 1.34 trillion L of water were withdrawn daily from groundwater and surface-water sources in the United States in 2010. The top water-use category was thermoelectric power generation, followed by irrigation, public supply, and industry (fig. 26). Water may undergo multiple treatment and distribution stages before, during, and after its intended end use. These stages are collectively referred to as the water-use cycle (fig. 27). The typical urban water-use cycle consists of the conveyance of water from its source to a point of treatment; treatment and distribution to residential, commercial, industrial, and other customers; and collection, treatment, and discharge of wastewater back to the environment. Water and wastewater treatments are not required for all uses of water. Depending on water quality and intended water use, water for and wastewater generated from irrigation, power plants, and industry may require little or no treatment.

Energy is consumed in each stage of the water-use cycle. Depending on the source of water (groundwater or surface water) and the distance and topography over which it is transported, large amounts of energy may be required to move water from its source to treatment plants. The conveyance of surface water by gravity is less energy intensive than pumping groundwater, but surface-water conveyances that require pumps can be quite energy intensive. In 2010, about 78 percent of the water used in the United States was supplied by surface water, and the rest was supplied by groundwater. Energy also is needed to treat and distribute water to end users; higher quality water generally requires less energy for treatment than poorer quality water. End users consume additional energy by heating and cooling water, circulating it for irrigation and other uses, and further treating it by processes such as reverse osmosis or ion exchange (water softeners). Eventually, water used in homes and businesses must be collected and treated before being returned to the environment or recycled, a process that also can use large amounts of energy depending on the level of treatment required.

Water-related energy use represents a substantial part of the total energy demand in the United States. A study done by the River Network estimated that in 2007 at least 13 percent of the Nation's electricity usage was for heating, moving, and treating water (Griffiths-Sattenspiel and Wilson, 2009). In California, water-related energy use consumes an estimated 19 percent of that state's electricity and 30 percent of its natural gas that is not used in power plants (California Energy Commission, 2005). Water-related energy usage in the United States is likely to increase. The Electric Power Research Institute projected about a 50 percent overall increase in energy usage for most freshwater supplies and treatment by the year 2050 (Electric Power Research Institute, 2002).

Despite the national importance of energy use for water, comprehensive national studies of this topic are lacking. According to the U.S. Government Accountability Office, comprehensive data about the energy needed for each stage of the water-use cycle are limited, and few nationwide studies have been conducted on the amount of energy used to provide drinking-water and wastewater-treatment services to users (U.S. Government Accountability Office, 2011a). In particular,

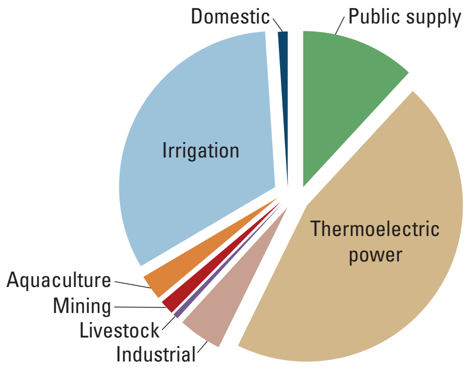


Figure 26. Total water withdrawals in the United States by category, 2010. (Maupin and others, 2014)

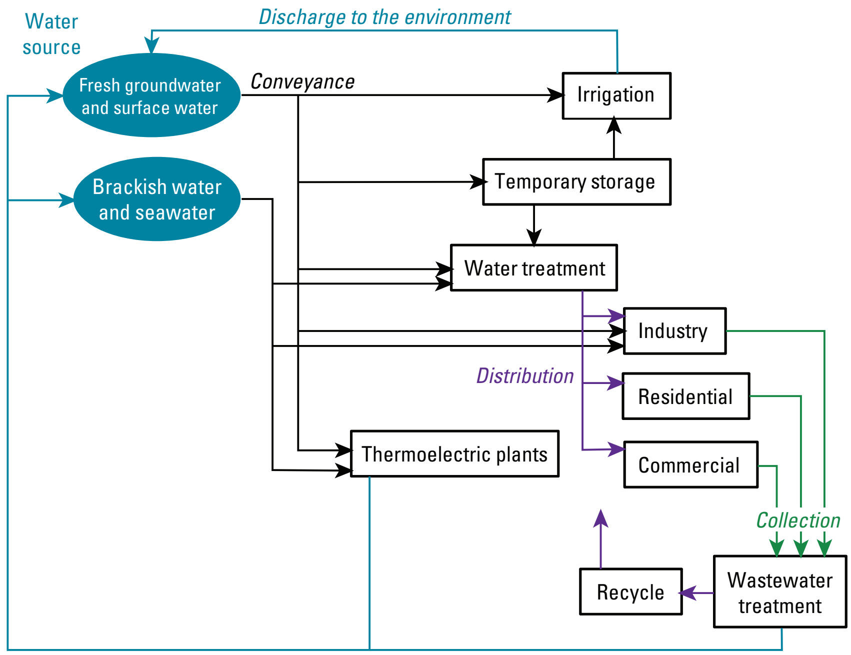


Figure 27. A generalized water-use cycle. The water-use cycle refers to the overall process of (1) collecting, developing, conveying, treating, and delivering water to end users; (2) using the water; and (3) collecting, treating, and disposing of wastewater.

energy consumption by water users is difficult to determine because electric and gas meters do not differentiate between the various uses of the customer. Nevertheless, the available data (Griffiths-Sattenspiel and Wilson, 2009; Sanders and Webber, 2013) provide a general understanding of the energy needs of the water-use cycle. The remainder of this section examines the energy requirements of the different stages of the water-use cycle—conveyance, treatment, distribution, end use, and wastewater collection and treatment.

Water Conveyance

Water conveyance refers to the withdrawal and transport of water from its source (such as an aquifer, river, or lake) to the point of treatment or use (fig. 27). The conveyance of groundwater generally is more energy intensive (that is, it requires more energy per unit volume of water) than the conveyance of surface water; pumping is required to withdraw groundwater from an aquifer, whereas often gravity can be used to move surface water from rivers and lakes to its point of use.

Groundwater

About 300 billion L/d of fresh and saline groundwater were withdrawn from aquifers in the United States in 2010. Groundwater withdrawals vary regionally and seasonally depending on intended water use and availability of both groundwater and surface water. The amount of energy consumed for groundwater withdrawals also varies. In western parts of the United States, most groundwater withdrawals occur during the growing season to sustain irrigated agriculture. California withdrew more fresh groundwater in 2010 than any other state, with about 71 percent of that water used for irrigation (Maupin and others, 2014). The electrical energy used to pump groundwater for irrigation in California in 2001 represented about 10 percent of all the water-related energy use in the state (California Energy Commission, 2005). In eastern parts of the United States, however, a larger percentage of groundwater withdrawals is for public supply, which means that withdrawals and associated energy consumption occur somewhat uniformly throughout the year. Florida had the sixth largest statewide fresh groundwater withdrawals in the Nation in 2010, with most of that water used for public supply.

The energy intensity of groundwater pumping depends on pumping depth and the efficiency of the pump. About 3.5 to 7 kWh of electricity are required to lift 1 million L of water 1 m, depending on pumping efficiency, so the deeper the groundwater, the more energy is required to bring that water to land surface. Public-supply wells consume an estimated average of 159 kWh per million liters (ML) of pumped groundwater (Electric Power Research Institute, 2002). Energy intensities for groundwater pumping from different depths in California were estimated to be in the range of 143 to 608 kWh/ML (Cohen and others, 2004). Declining water levels in aquifers, whether from over pumping or drought, generally result in rising energy costs for pumping. The two most heavily pumped aquifer systems in the United States, the High Plains aquifer in the west-central United States and the Central Valley aquifer system in California, have already experienced large water-level declines. To some extent, the increased energy costs associated with pumping deeper groundwater could be offset by using more efficient equipment. High-efficiency groundwater pumps are more expensive than standard pumps, but they use 10 to 30 percent less energy; the extra cost typically is recovered quickly through energy savings and lower maintenance costs (Electric Power Research Institute, 2009).

Pumping groundwater from aquifers for water supply (left) is much more energy intensive than moving surface water by gravity-fed pipelines and canals (right).

The volume of groundwater withdrawals and associated energy use at any location could vary as a result of changes in climate. Drought, for example, could lead to increased energy use by necessitating more overall groundwater pumping, both for agricultural uses and to offset reductions in surface-water supplies used for drinking water or for cooling at thermoelectric power plants, which could in turn lower water levels in aquifers. In the Central Valley of California, the volume of groundwater pumped for agriculture during a typical dry year was more than twice the volume pumped during a typical wet year (Faunt, 2009). Managed aquifer recharge is a water-management option that can help address problems at areas that experience periodic water stresses (see Box L—Managed Aquifer Recharge of Recoverable Water).

Surface Water

In 2010, about 1.04 trillion L of fresh and saline surface water were withdrawn daily from rivers, lakes, and other water bodies in the United States, more than three times the volume of groundwater withdrawals. Surface-water withdrawals vary by region and season across the Nation for some of the same reasons that groundwater withdrawals vary. California had the largest volume of state-wide fresh surface-water withdrawals in the Nation in 2010, with approximately 77 percent of that water used for irrigation during the growing season. In other western States, such as Colorado, upwards of 90 percent of the fresh surface-water withdrawals are used for irrigation. In eastern parts of the United States, a much larger percentage of withdrawn surface water is used for cooling at thermoelectric power plants, a process that requires year-round withdrawals. Illinois, for example, had the fourth largest volume of fresh surface-water withdrawals in the Nation in 2010, with about 88 percent of that water used for cooling (Maupin and others, 2014).

Despite the large volume of surface-water withdrawals, the energy intensity of this activity can be quite low for gravity-fed conveyances. Gravity-fed conveyances provide surface water to some of the largest metropolitan areas and agricultural regions of the Nation. The drinking-water supply for New York City, for example, consists in part of a network of reservoirs located as far as 200 km from the city, yet 95 percent of the conveyance is gravity fed. Another gravity-fed conveyance, the roughly 130-km-long All-American Canal, is one of the largest irrigation canals in the world and transports water from the Colorado River near Yuma, Arizona, to irrigated cropland in the Imperial Valley in southeastern California (Loeltz and Leake, 1979).

Not all surface-water conveyances, however, can be fed by gravity. Delivery of water from northern to southern California by the State Water Project, for example, requires pumping the water nearly 600 m up and over the Tehachapi Mountains at the Edmonston Pumping Plant. In 2000, the energy intensity of that operation was about 1,850 kWh/ML, more than 10 times the previously cited average energy intensity for groundwater pumping at municipal supply wells (California Department of Water Resources, 2002). Thus, topography is an important control on the energy intensity of surface-water conveyances.

The energy intensity of water conveyance also is dependent on the efficiency of the infrastructure. Leaks from unlined canals can be substantial, as can evaporation from the open water surfaces of large reservoirs. The energy costs associated with leaks and evaporation are greater for canals, pipelines, and reservoirs filled with water by pumping than they would for those that are gravity fed because of the increased cost of pumping water for a prescribed amount of delivered water. The potential for leakage and evaporation generally increase as the distance of water transport in canals and pipelines and the water residence time in reservoirs increase. The annual evaporative loss from Lake Mead, about 720 trillion L (Moreo and Swancar, 2013), is equivalent to about 2 percent of the average volume of the reservoir. Conveyances to Lake Mead are gravity fed, so leaks and evaporation do not add substantially to the amount of energy required to deliver water to the lake. The evaporation from Lake Mead can be viewed as a lost source of energy generation, however, because the water that evaporates does not pass through the Hoover Dam hydroelectric turbines. In some instances, it is economically feasible to stop or reduce the loss of water from surface-water bodies.

Continued on page 60

At the Edmonston Pumping Plant, water is pumped up nearly 600 m as part of the California State Water Project.

Managed Aquifer Recharge of Recoverable Water

The ability to store water in times of plentiful precipitation and recover water in times of scarcity is highly desirable for a number of reasons. Interest in storage and recovery systems is likely to expand because of growing human populations and the risk of increased climate variability. In the past, this water-management objective was often met by constructing dams to impound surface water. Few large dams have been constructed in the United States since the middle of the 20th century. Increasingly, managed aquifer recharge is being used to store and recover water for later use. In addition to economic and environmental benefits, underground storage systems avoid the large water losses that occur in surface reservoirs as the result of evaporation.

Managed aquifer recharge (MAR) is the purposeful recharge of water into an aquifer. The intent of the operation is usually to store water for future recovery and use; however, MAR is also used to inhibit saltwater intrusion and land subsidence. Surface water, groundwater, treated wastewater, and other recycled water have all been used to recharge aquifers in MAR systems. The chosen type of recharge water and level of pre-injection treatment depend in part on the intended use of the water, the availability of water sources, and the water's chemical compatibility with aquifer solids and native groundwater. Depending on site conditions, the host aquifer is recharged through constructed recharge basins, direct recharge wells, or shallow wells completed above the water table. Water can be recovered by extraction wells that pump water out of the aquifer. The recovered water might or might not undergo treatment prior to use, depending on the extent of the chemical alteration of the water while in storage in the aquifer and the intended use of the water. In some MAR systems, the chemical quality of stored water actually improved during its residence time in the aquifer (National Research Council, 2008b).

Managed aquifer recharge systems are located throughout the United States and the number of systems is growing rapidly (Pyne, 2005; National Research Council, 2008b). Most of the systems are located in coastal areas and arid regions of the southwestern United States, but some MAR systems also are located in humid, interior regions of the country. Most MAR systems are used for municipal water supply, but others are used for irrigation and cooling supplies and to control saltwater intrusion. Managed recharge is done at many different scales. In Orange County, California, managed recharge offsets pumping demands on the groundwater basin that provides over half the water needs for 2.4 million people (Orange County Water District, 2014). The advanced treatment and recharge process uses less than half the energy that it takes to transport an equivalent amount of water from northern California and less than one third of the energy required to desalinate that much water. On a smaller scale, the City of Tigard, Oregon, with a population of 48,695 in 2012, injects water into a local aquifer during the winter months and pumps it back out for use in the summer (City of Tigard, 2014). The energy intensity of MAR systems has not been examined in detail but should be similar to that of groundwater with some additional energy required for conveyance of water to and from the recharge site. As demand for water increases, MAR systems could be a more energy-efficient option than alternatives such as conveying water over long distances or treating saline water.

Sand Hollow Reservoir, constructed for managed aquifer recharge in southwestern Utah, has become a popular destination for boating and fishing.

The Coachella Canal lining project in southern California replaced 56 km of unlined canal with concrete-lined canal and in the process saved about 90 million L/d of water that otherwise would have been lost to seepage (San Diego County Water Authority, 2013). Much of the conserved water provides a new water supply for San Diego County; it is worth noting, however, that some of the water that was lost to canal seepage prior to the project actually helped to replenish local groundwater supplies in the vicinity of the canal.

Water Treatment

Water for commercial, industrial, and residential purposes usually requires treatment prior to or during use (fig. 27). The energy intensity of water treatment depends on the water source, quality of the source water, the intended use of the water (not all uses require treatment to drinking-water standards), and the chosen treatment process. The age of water-treatment infrastructure also could affect overall energy intensity because old infrastructure may be less energy efficient or could leak more than new infrastructure. With respect to freshwater, the treatment of groundwater to drinking-water standards commonly is less energy intensive than the treatment of surface water. Groundwater often only requires disinfection, such as by chlorination, whereas surface-water treatment is a multistage process that usually includes not just disinfection but also processes like flocculation, sedimentation, and filtration to coagulate and remove sediment and other particles (table 9 and fig. 28). The energy intensity of groundwater chlorination is estimated to be less than 2.6 kWh/ML, whereas the energy intensity of multistage surface-water treatment is estimated to be about 26 kWh/ML, or more than a 10-fold increase over the energy intensity of groundwater treatment (Electric Power Research Institute, 2002). Neither of these estimates includes the energy required to distribute treated water to end users, which can have a much higher energy intensity than the water-treatment process itself; distribution is discussed in a subsequent section. While energy sources other than electricity are occasionally used for water treatment, 93 percent of water providers receive 90 percent or more of their operating energy from electricity (Griffiths-Sattenspiel and Wilson, 2009).

These estimates for the energy intensity of water treatment assume a freshwater source, yet increasing interest is being given to saline groundwater and seawater as drinking-water sources in areas that lack adequate supplies of freshwater. Total desalination capacity in the United States in 2005 was about 57,000 million L/d, or about 3 percent of the total water withdrawals for public supply (National Research Council, 2008a). Two-thirds of that desalination capacity is used for municipal water supply. The states with the largest installed desalination capacity are Florida, California, and Texas, all coastal states with large populations, and Arizona, an arid state. Desalination of groundwater and seawater to drinking-water standards requires a substantial amount of energy. In California, the energy intensity for treatment of saline groundwater is about 1,060 to 2,600 kWh/ML; treatment of estuarine water and seawater requires an intensity of about 2,600 to 4,000 kWh/ML. These energy intensities represent increases of as much as 1,500 and 150 times the intensities for treating fresh groundwater and surface water, respectively. When the

Table 9. Percentage of community water-treatment plants using different treatment schemes.

[Data from U.S. Environmental Protection Agency (2002). Values are percentages]

Treatment practice	Groundwater plants	Surface-water plants
Disinfection only	55	11
Disinfection and other treatment	45	89

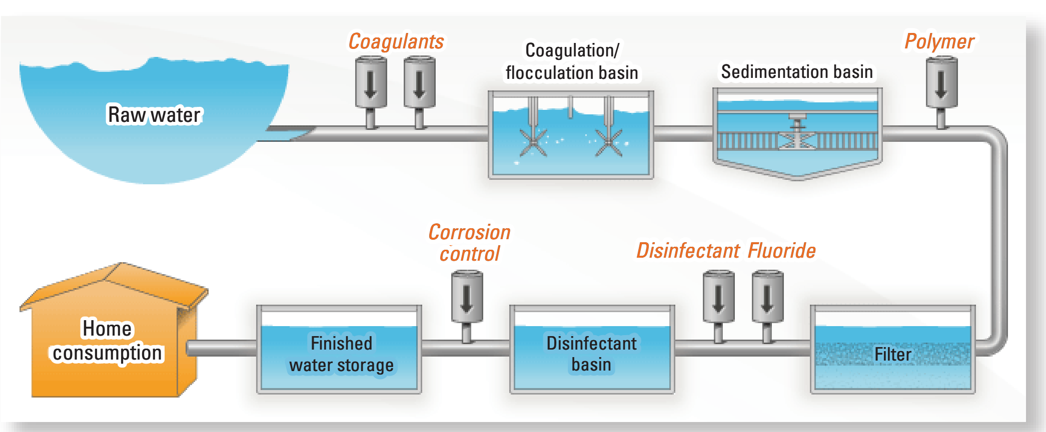


Figure 28. Schematic representation of the process used by the Denver Water public agency to treat surface water. (Denver Water, 2014)

energy intensities for conveyance and treatment are combined, however, the differences in intensity between the water sources can be much less (fig. 29).

The energy intensity of water treatment is likely to decrease as more efficient technologies are adopted. New technologies related to pump design and pipeline optimization could save 5 to 30 percent of the energy associated with those components of a treatment plant, potentially saving the cost of millions of kilowatthours of electricity each year (table 10). Advanced treatment technologies associated with disinfection, such as ozone and ultraviolet-light treatments, could save 10 to 30 percent of the energy associated with chlorination. These new treatments are important because the use of chlorine to disinfect water has come under scrutiny as it could generate disinfection byproducts such as chloroform that potentially can be harmful to human health (Rostad, 2007). Advanced treatment technologies related to reverse osmosis and membrane distillation could save even more energy (50 percent or more) when used for desalination.

Regulatory standards also affect the energy intensity of water treatment. The Safe Drinking Water Act governs what concentrations of selected chemical, radioactive, and biological constituents are safe in public drinking water. More restrictive standards (that is, lower limits on concentrations of some constituents) generally require more energy-intensive treatment methods. As an example, arsenic concentrations in drinking water have long been a concern. In 2002, the U.S. Environmental Protection Agency finalized a reduction in

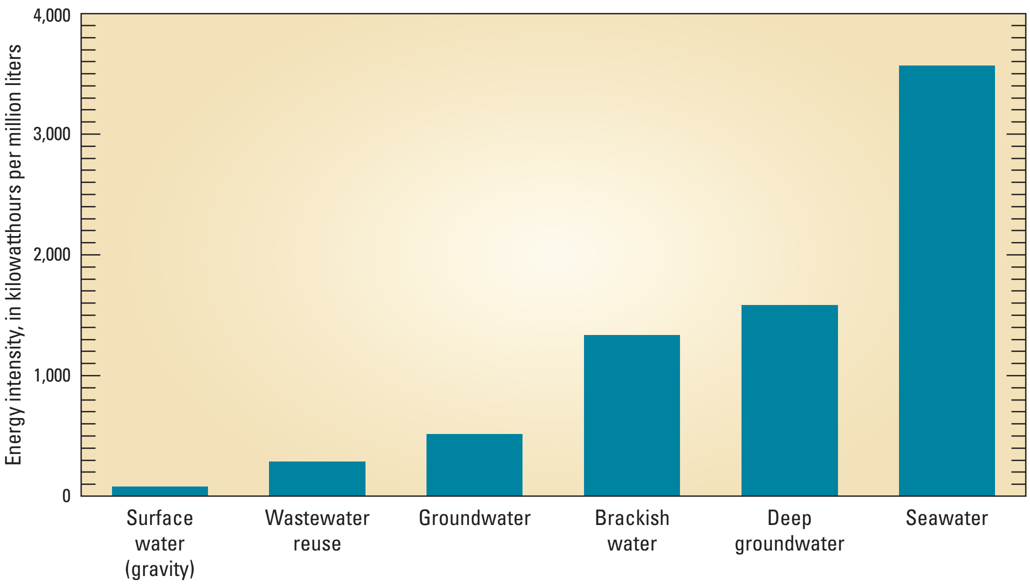
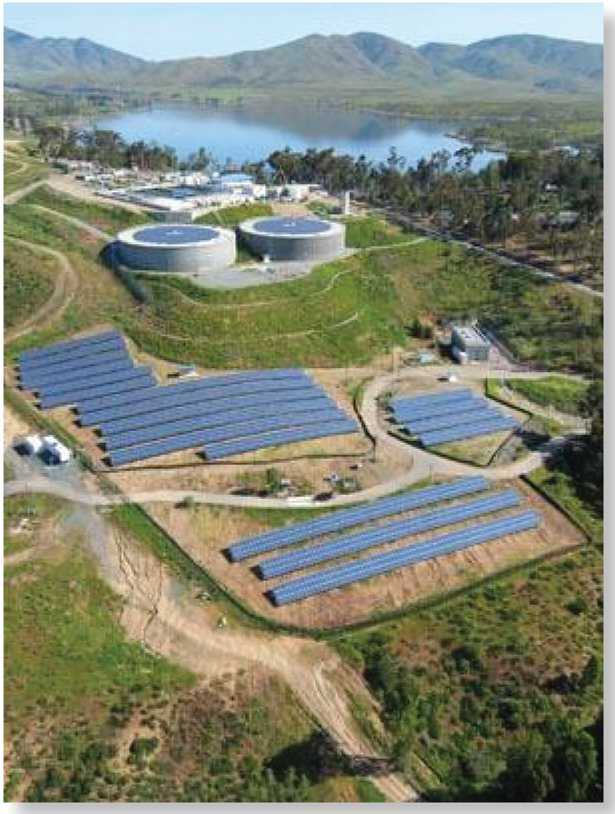


Figure 29. Typical energy intensities associated with the conveyance and treatment of water, by source. (Modified from Electrical Power Research Institute, 2009)

Table 10. Estimated energy savings for selected water technologies.

[Data from Electric Power Research Institute (2009). %, percent; kWh/yr, kilowatthours per year]

Technology	Percent savings potential	Potential electrical energy savings in public water supplies (million kWh/yr)
High-efficiency pump/motor systems	10 to 30% of pumping energy	2,600–7,800
Pipeline optimization	5 to 20% of pumping energy	1,300–5,200
Advanced membranes	15 to 25% of treatment energy	117–195
Advanced ozone	10 to 20% of treatment energy	572–654
Advanced ultraviolet	10 to 30% of treatment energy	515–544
Advanced reverse osmosis	50% of desalination treatment energy	2,400
Capacitive deionization	50% of brackish water treatment energy	1,000
Membrane distillation	66% of desalination treatment energy	3,200



The City of San Diego, California, installed a 1.5 million kWh/yr solar photovoltaic energy system at its Otay Water Treatment Plant. The solar system has the capacity to provide enough energy to power the plant's treatment of about 130 million L of water each day, thereby avoiding the release of more than 0.454 million kg of carbon dioxide to the atmosphere each year (U.S. Department of Energy, 2010).

the arsenic standard from 50 to 10 micrograms per liter (µg/L). That standard went into effect in 2006. The energy costs associated with upgrading water-treatment facilities to meet the lower arsenic standard were a particularly relevant issue for suppliers of groundwater because groundwater tends to have higher arsenic concentrations than surface water. A study of the quality of water from public-supply wells found that about 10 percent of the source-water samples (groundwater collected before the point of treatment) had arsenic concentrations that exceeded the new 10-µg/L standard (Toccalino and Hopple, 2010). Less than 1 percent of the samples exceeded the old standard (50 µg/L), so lowering the standard meant that more wells would be out of compliance unless some type of action was taken. Several processes are available for removing arsenic from water, such as an activated alumina treatment, which can require up to 26 kWh/ML (U.S. Environmental Protection Agency, 2003), a substantial increase in energy requirements for those facilities that were required to upgrade their treatment process to meet the reduced arsenic standard.

Water Distribution

Distributing treated water to end users requires more energy than the water treatment process itself. The Electric Power Research Institute estimated an energy intensity of about 317 kWh/ML for distributing drinking water from surface-water treatment plants with a capacity of at least 3.8 million L/d (Electric Power Research Institute, 2002), whereas the energy intensity of the treatment process is about 26 kWh/ML. For groundwater, the estimated intensity for distribution was also about 317 kWh/ML, but the energy intensity of treatment by chlorination is about 2.6 kWh/ML. The energy intensity of water distribution depends to a large extent on the distance and elevation of the treatment plant in relation to end users. As indicated previously, about 3.5 to 7 kWh are required to lift 1 million L of water 1 m; pumping water requires energy.

The efficiency of water delivery systems also affects the associated energy requirements. As discussed in the section "Water Conveyance," pipelines have the potential to develop leaks. As water loss from a delivery system increases, the amount of energy required to provide the prescribed amount of water received at the destination increases. The potential for water leakage often increases with the age of the distribution system. Water utilities are continually upgrading distribution systems, but the task is very large and inevitably there will be old water mains in some distribution systems. In its 2000 Community Water System Survey, the U.S. Environmental Protection Agency estimated that community water systems maintain more than 3 million km of distribution mains. Seventy-eight percent of those mains were less than 40 years old, 18 percent were 40 to 80 years old, and 4 percent were more than 80 years old (U.S. Environmental Protection Agency, 2002). The efficiency of the delivery of treated water is of particular concern because of the relatively high energy cost for treatment and delivery. Loss from water mains during delivery are commonly in the range of 10 to 60 percent (Passarello and others, 2012), implying that if all leaks were repaired, then water and related energy use could be reduced by more than one half. A mere 5 percent reduction in water distribution system leakage in the United States could save about 1 billion L/d of water and 313 million kWh of electricity annually (Griffiths-Sattenspiel and Wilson, 2009).

End Use

Once water arrives at a residence or place of business, it may undergo additional processing for heating, further purification, or pressurization. All of these processes consume energy. The hot showers and baths we enjoy, in particular, consume substantial amounts of energy. The energy intensity of heating water for bathing or dishwashing is about 42,000 to 54,000 kWh/ML (table 11), which is about 10 times higher than that for desalination of seawater (fig. 29). In fact, water

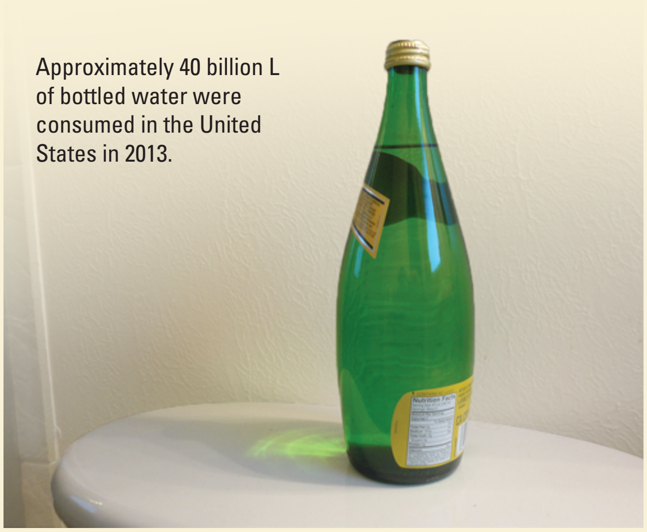
M The Energy Intensity of Bottled Water

Bottled water is a popular beverage in the United States. In 2011, consumers purchased more than 34 billion L of bottled water. Energy is required to produce, treat, package, and transport that water to consumers. Energy also is required to make the plastic bottles that contain the water. Gleick and Cooley (2009) examined the energy intensity of bottled water and determined that delivering bottled water to the end user requires up to 2,000 times more energy than delivering tap water (which includes the typical energy costs of conveyance, treatment, and distribution of tap water). The two components of bottled-water delivery that require the most energy are transportation of the water from the bottling plant to the point of sale and manufacture of the plastic bottles (table M–1). Some brands of bottled water have water sources in the United States, but others are sourced in Europe, the South Pacific region, and other distant locations. According to the analysis by Gleick and Cooley (2009), the energy costs of transporting bottled water from Europe or the South Pacific to markets in the United States are about 3 to 4 times greater than the energy costs for transportation from local sources in the United States. Although the energy intensity associated with bottled water is large, the actual volume of water that is consumed is small when compared to the volume of tap water consumed—the volume of bottled water consumed in the United States in a year would only supply our national tap water needs for about 5 hours, on the basis of 2011 bottled-water sales and groundwater and surface-water withdrawals for public and domestic supplies in the United States in 2010.

Table M–1. Energy requirements for producing bottled water.

[Data from Gleick and Cooley (2009). kWhth/L, kilowatthour of thermal energy per liter of water]

Stage of production	Energy intensity (kWhth/L)
Manufacture of plastic bottle	1.1
Treatment at bottling plant	2.8×10^{-5}–0.006
Filling, labeling, and sealing of bottle	0.003
Transportation: 3 scenarios	0.39–1.6
Cooling	0.06–0.11
Total	1.6–2.8
Typical energy intensity of tap water	0.001



Approximately 40 billion L of bottled water were consumed in the United States in 2013.

heating is the most energy-intensive process in the water-use cycle. Residential and commercial hot-water heaters account for about 79 percent of all energy used in the water-use cycle for those sectors, far exceeding the combined energy consumption associated with the conveyance, treatment, and delivery of water to the end user (Griffiths-Sattenspiel and Wilson, 2009). More cold water, mostly for flushing toilets and landscape irrigation, is used at residences than hot water, but cold-water use has a relatively low energy intensity. Similarly, other end-use processes, such as pressurization or water purification, consume very little energy relative to the energy that is used to heat water.

Agricultural water generally is less energy intensive than urban water. Nevertheless, saving water by using more efficient irrigation techniques or by growing crops that use less water could save energy associated with the conveyance of water to fields. Surface flood irrigation of cropland has an average irrigation efficiency (the percent of applied water that is actually taken up by the crop) of only 50 percent, whereas average efficiencies for center-pivot sprinklers and subsurface drip irrigation systems are 85 and 90 percent, respectively (Electric Power Research Institute, 2009). Much of the water applied to fields using flood irrigation percolates below the root zone and is not used by the crop.

As with other of components of the water-use cycle, efficiencies gained through technological upgrades in equipment and minimization of system leaks result in direct energy and water savings for end users. Of the various water-cycle components, however, end use is unique in that water conservation by end users also results in energy and water savings at the early stages of the water-use cycle (conveyance, treatment, and distribution) and at the late stages (wastewater collection and treatment). An added benefit of water conservation is that more water could remain in aquifers, streams, lakes, and other water bodies for environmental uses.

In urban areas, replacing the old equipment that moves or uses water, such as plumbing and toilets, with more efficient models would result in substantial energy and water savings (table 12). The California Energy Commission estimated that the installation of ultra low-flow toilets in residences within the state would result in a savings of about 3 billion kWh of electricity over 25 years (table 12). The use of recycled water could save further energy and water by reducing the demand for new, more energy-intensive water supplies (see Box N—Recycled Water in California).

Residential and commercial hot-water heaters used for hot tubs, dishwashers, baths, and showers account for about 79 percent of all water-related energy consumption for those sectors. The U.S. Department of Energy offers a number of tips for reducing energy consumption associated with hot-water heaters; these include using less hot water, turning down the water heater's thermostat, installing low-flow faucets and showerheads, and installing a more energy-efficient heater, such as an on-demand tankless heater or a heater that is powered by solar or geothermal energy. (U.S. Department of Energy, 2013c)

Table 11. Estimated energy intensity of heating water for selected residential water uses.

[Values are in kilowatthours per million liters of water]

Water-use category	Energy intensity[1]
Dishwasher	53,800
Bath	42,000
Shower	39,300
Faucet	39,100
Clothes washers	15,000
Leaks	14,400
Toilet	0
Landscape irrigation	0

[1]Based on data from Griffiths-Sattenspiel and Wilson (2009) and DeOreo and Mayer (2001).

Table 12. Energy value of water saved as the result of the implementation of selected water-efficiency measures in California, 2004.

[Data from California Energy Commission (2005). ML, million liters; kWh, kilowatthours; na, not applicable]

Efficiency measure	Annual savings		Useful life (years)	Life-cycle electricity savings (kWh)
	Water (ML)	Electricity (kWh)		
Residential plumbing retrofit	1,180	2,814,000	5	14,070,000
Metering	6,000	14,317,200	11	157,489,200
High-efficiency washing machine rebate	1,200	2,860,100	15	42,901,500
Residential ultra low-flow toilets	49,000	117,184,600	25	2,929,615,000
Large landscape conservation programs	20,100	34,595,450	10	345,954,500
Commercial, institutional, and industrial ultra low-flow toilets	980	2,328,300	25	58,207,500
Commercial, institutional, and industrial conservation programs	18,200	43,433,300	12	521,199,600
Statewide totals	96,660	171,771,350	na	4,069,437,300

Wastewater Collection

Wastewater collection refers to the transfer of wastewater from its point of generation in homes, businesses, and elsewhere to a wastewater treatment plant. The energy intensity of wastewater collection on average is about 40 kWh/ML (California Energy Commission, 2005), which is relatively small compared to the energy intensity of water distribution (about 317 kWh/ML). Wastewater treatment plant operators generally try to place their facilities at a lower elevation than that of their customers to take advantage of gravity and thereby minimize pumping. Leakage rates from wastewater collection networks, or sewers, are generally considered to be less than those from water mains because these systems are not pressurized. Leakage rates for wastewater networks are typically in the range of 5 to 20 percent (Schirmer and others, 2013), but rates as high as 56 percent have been reported (Rutsch and others, 2008). Leakage from sewer lines could affect the quality of the receiving groundwater and surface water (Lerner, 2002; Schirmer and others, 2013) and potentially the treatment costs for downstream water users.

An additional concern is that low pressures within sewer systems can allow groundwater to seep into leaky pipes, thus adding to the amount of water that must be treated and the amount of energy consumed at wastewater treatment facilities (Wittenberg and Aksoy, 2010). Groundwater seepage can be particularly problematic during intense precipitation events, when it is not uncommon for stormwater to enter sewer systems. There is no way to differentiate between stormwater and sewage once it enters a sewer system, so both are processed at the wastewater treatment plant. Because the energy used to treat wastewater is proportional to the influent flow rate, increased flows caused by stormwater result in increased energy use by the plant. Excessively large stormwater inflows to wastewater treatment plants can potentially exceed the treatment capacity of the plants, resulting in the release of untreated wastewater into the environment.

Wastewater Treatment

Approximately 40,000 publicly or privately owned wastewater treatment plants operate in the United States (Solley and others, 1998). These plants are designed to remove physical, biological, and chemical contaminants from wastewaters received from residential, commercial, and industrial sources (as described in the previous section, treatment plants sometimes receive storm runoff as well). A number of techniques may be used for treating wastewater, most of which require energy. New processes are continually being developed in attempts to reduce energy requirements; in fact, recently developed techniques can capture and use energy contained in wastewater.

Multiple processes are applied at most municipal wastewater treatment plants, including screening out debris, removing suspended solids and grease, removing nutrients, chlorination, filtering, and dechlorinization (fig. 30). During these processes, solids are separated from the water, oxygen is added to promote biologic activity, water is disinfected with chlorine or ultraviolet light, and nutrients and other chemicals are filtered out.

The amount of energy needed to treat wastewater depends on the plant size and the specific treatment methods that are applied. Energy use for public and private wastewater treatment plants was 74 billion kWh in 2005, or about 15 percent of the energy used in the entire water-use cycle for the residential and commercial sectors (Griffith-Sattenspiel and Wilson, 2009). Energy intensity generally decreases with increasing plant size because of economies of scale, but the intensity increases with increasing level of treatment (Electric Power Research Institute, 2002). The most energy-intensive process is the treatment of the extracted solid materials, often referred to as sludge or biosolids. The solids are collected into sludge digesters where anaerobic reactions and heat are used to degrade biological contaminants. Sludge digesters can consume 30 to 80 percent of all electricity used at wastewater treatment plants (Center for Sustainable Systems, 2013).

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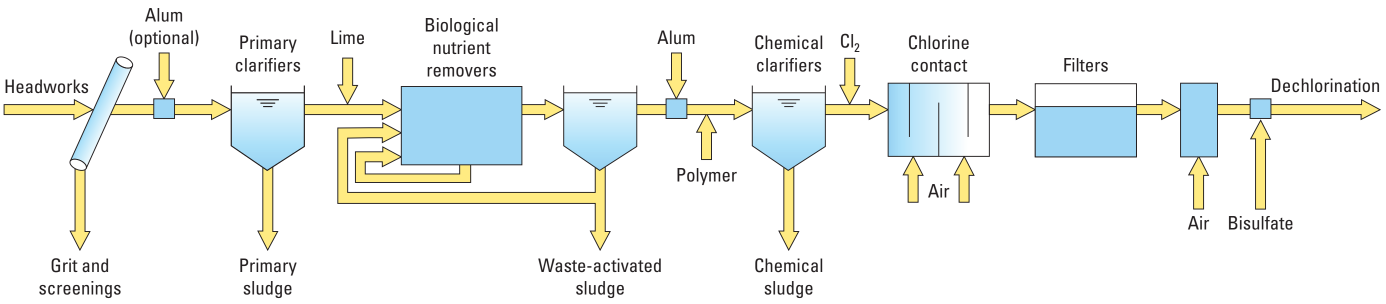

Figure 30. Summertime treatment processes at Clean Water Services' wastewater treatment facility in Durham, Oregon. (Diagram reproduced with permission from Clean Water Services)

N Recycled Water in California

The California Sustainability Alliance defines recycled water as municipal, industrial, or agricultural wastewater, which, as a result of treatment, is suitable for a direct beneficial use or a controlled use that would not otherwise occur. Recycled water represents the fastest growing new source of water in California (California Energy Commission, 2005). This trend is related to the large volume of treated wastewater that is potentially available for reuse and the fact that the energy intensity of recycled water is small relative to that of other water sources.

California water agencies used about 0.6 trillion L of recycled water in 2001; by 2030, usage is estimated to be 2.2–2.7 trillion L (California Department of Water Resources, 2009). The primary uses were for agriculture irrigation, landscape irrigation, and groundwater recharge projects (fig. N–1). In general, the uses of recycled water are broadly grouped into direct and indirect uses (fig. N–2). Direct uses are those intentional uses such as irrigation and groundwater recharge that use water directly from the wastewater treatment plant (fig. N–2). Indirect uses are those unintentional or intentional uses of treated wastewater that has spent time in an aquifer or surface-water body such as a stream or wetland. In reality, indirect use of treated wastewater has occurred for many years across the United States where treated wastewater is discharged to rivers and septic-tank effluent recharges aquifers and where downstream users withdraw that water for new purposes.

Recycled wastewater is energy efficient because conveyance from a source is not required and wastewater has to undergo some level of treatment anyway. Some energy might be required for extra treatment, depending on the intended use, and for distribution to the end user. Wastewater that has

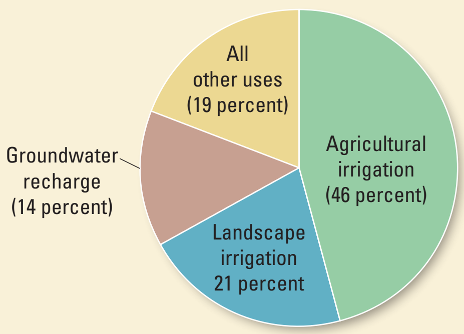

Figure N–1. The State of California's use of recycled wastewater, 2001, as a percentage of the total amount of about 0.6 trillion liters. Most of the recycled wastewater was used for agricultural and landscape irrigation and for groundwater recharge projects. (Data from the California Department of Water Resources, 2009)

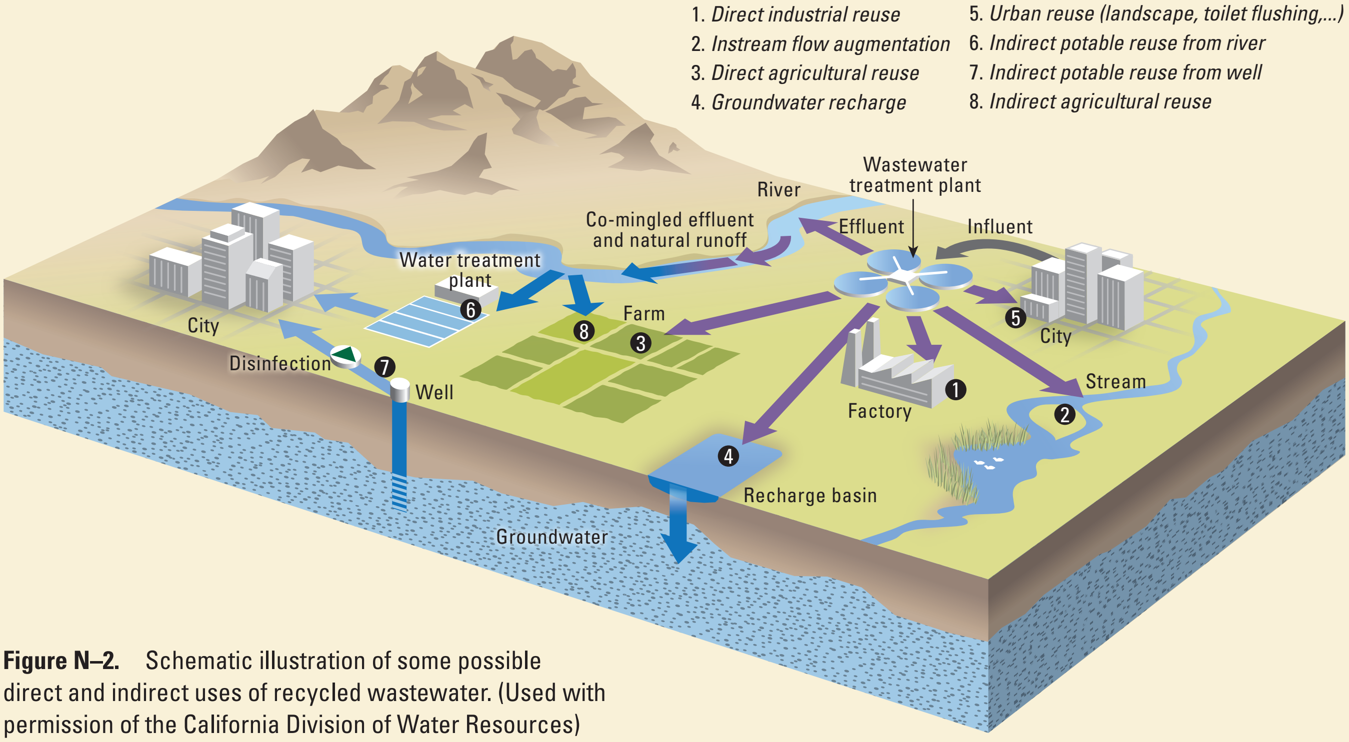

Figure N–2. Schematic illustration of some possible direct and indirect uses of recycled wastewater. (Used with permission of the California Division of Water Resources) undergone tertiary treatment is acceptable for a broader group of uses than wastewater that has undergone only secondary treatment. If wastewater treated to a secondary level was intended for a more restricted use such as the irrigation of food crops, then additional energy would be required to treat the water to a higher level before it was used. Despite the additional energy that might be needed to use treated wastewater, it is still a less energy-intensive source of water than many others in California (fig. N–3).

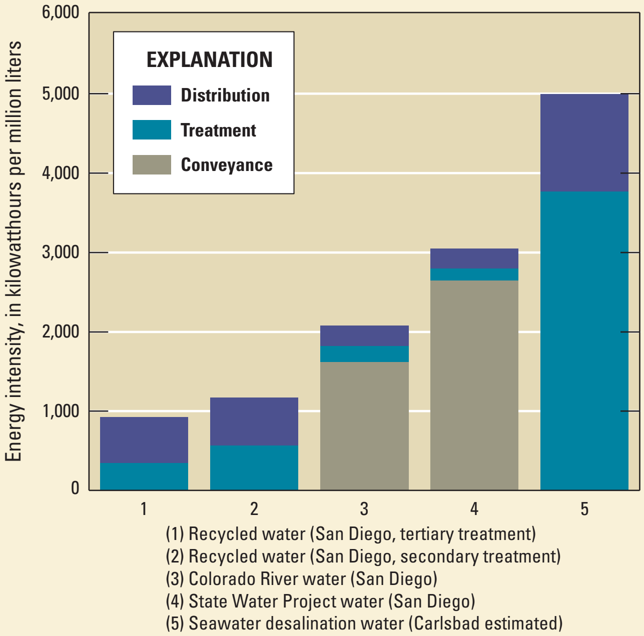

Figure N–3. Relative energy intensity of selected water sources in southern California. (Modified from California Sustainability Alliance, 2008)

Aerial view of the Carson, California, West Basin water recycling facility.

The Clean Water Act governs the discharge of pollutants into the waters of the United States. As with the Safe Drinking Water Act, new regulatory standards could alter the energy intensity of treatment in the future. Of particular concern are chemicals that the U.S. Environmental Protection Agency refers to as contaminants of emerging concern (CECs) (U.S. Environmental Protection Agency, 2014b). These are chemicals that have only recently been detected in surface water and groundwaters and whose risk to human health and the environment are unknown. Included in this group are pharmaceuticals, personal care products, and perfluorinated compounds. Studies have found that the level of removal of those chemicals from wastewater is dependent on factors such as the type of chemical compound and the treatment process. One study examined the treatment efficiency for removing 55 CECs from wastewater streams; on average, standard treatment processes removed over 85 percent of the CECs (Kasprzyk-Hordern and others, 2009). If more restrictive regulatory standards are put in place for CECs, then more energy-intensive, enhanced treatments will likely need to be implemented to meet those standards. This example reinforces the message that protecting water quality saves energy.

Organic matter contained in wastewater can be an important and useful source of energy. According to the Water Environment Research Foundation, the energy content of wastewater and biosolids exceeds the energy needed to treat that wastewater by a factor of 10 (Water Environment Research Foundation, 2011). As of 2011, 104 wastewater treatments plants with anaerobic digesters in the United States were using the microbial methane produced in their digesters to generate electricity and heat; the combined capacity of these plants is 190 MW (U.S. Environmental Protection Agency, 2011a). This power-generating process could be carried out economically at hundreds of additional treatment plants. Development of “high performance” microorganisms that anaerobically digest waste more efficiently could increase the methane yield at wastewater treatment plants. Recent studies indicate that fully anaerobic treatment processes could generate substantially more methane than conventional aerobic/anaerobic treatment processes, possibly to the point of making wastewater treatment a net producer of energy (McCarty and others, 2011). Capturing the methane generated in treatment has the added benefit of eliminating direct release of that greenhouse gas into the atmosphere. Fully anaerobic wastewater treatment offers increased potential for achieving energy and cost savings, but more work needs to be done before this technology is adopted by the wastewater industry.

Septic systems are onsite wastewater treatment systems commonly used at homes whose plumbing is not connected to a centralized wastewater treatment plant. According to the 2010 U.S. Census, about 19 percent of the estimated 115 million occupied homes in the United States used some type of onsite wastewater treatment system (U.S. Census Bureau, 2014). The treatment processes and equipment used in septic systems are quite simple in comparison with most centralized wastewater treatment plants, so septic systems typically have very low energy intensities. When properly designed, constructed, and maintained, septic systems can provide good treatment of wastewater, but septic systems that are not operating properly have the potential to degrade groundwater and surface-water quality (Katz and others, 2011), which ultimately could lead to higher energy costs associated with treatment for downstream water users.

Demonstration wetland at Henderson, Nevada, where vegetated hummocks were built into the wastewater treatment wetland to improve its effectiveness and sustainability, as well as provide quality wildlife habitat.

Summary of Water-Related Energy Use

Energy consumed in providing and treating water represents an important part of the Nation's energy demand. As discussed in the preceding sections, energy is required for transporting water and for treating it before, during, and after use. The actual amount of energy required for all stages of the water-use cycle varies greatly across the country depending on location of water source and use, quality of water, intended use, and technologies that are employed. Total water-related energy consumption in the United States in 2005 for residential and commercial uses is estimated to be equivalent to about 482 billion kWh of electricity (fig. 31), or about 15 percent of all the electricity used in the United States. Details on industrial water-related energy use are lacking because much of that information is proprietary and unavailable to the public (Sanders and Webber, 2012), and water-related energy consumption for the transportation sector is assumed to be negligible. The most energy-intensive treatment stage of the water-use cycle for the residential and commercial sectors is heating water; hot-water heaters account for about 79 percent of water-related energy consumption. Reducing the use of hot water and improving techniques for heating water might be the most effective ways for reducing water-related energy consumption in the United States.

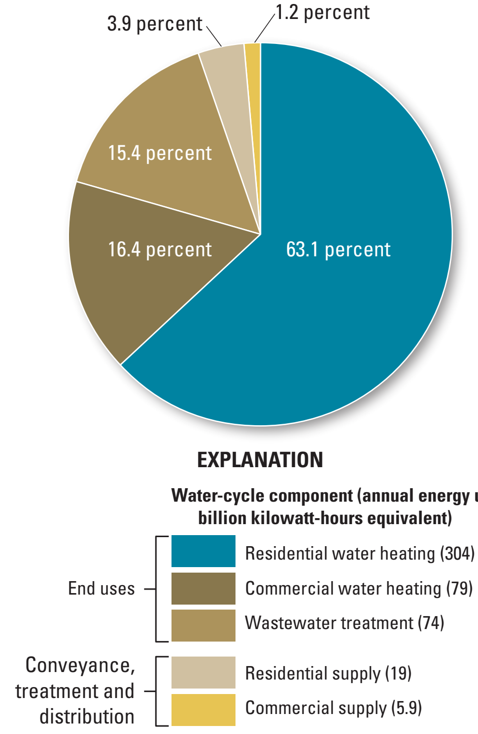

Figure 31. Annual water-related energy use in the residential and commercial sectors of the United States, 2005. Energy use in kilowatthours of equivalent electricity takes into account the fact that about 50 percent of the energy used for heating water comes from natural gas. (Griffiths-Sattenspiel and Wilson, 2009)

Science for Addressing the Water-Energy Nexus

Establishing sustainable supplies of freshwater and energy for future generations are goals that have widespread support within the United States. Earlier sections of this report presented discussions of the use of water for energy development and the use of energy for water development. Readily apparent in those discussions is the high degree of uncertainty in estimates of energy-related water consumption and water-related energy use. This uncertainty clouds our understanding of important issues and complicates efforts to ensure sustainable supplies of water and energy. This section addresses the earth science aspects of the water-energy nexus; it presents a review of current data-collection and research efforts and an examination of how enhanced efforts can reduce the uncertainty in our understanding of important water-energy issues and promote sustainable use of precious resources. Data collection, data interpretation, and research are all closely intertwined. For convenience, water- and energy-related issues are addressed in the following sections under the two broadly overlapping themes of monitoring and assessments and earth science research.

A spring-fed stream in the Two-Medicine drainage of Glacier National Park. Springs offer services such as water for humans, vegetation, and local and migratory wildlife.

Monitoring and Assessment

Monitoring Networks

Hydrologic, climatological, environmental, seismic, and other types of data are collected across the United States for a wide range of purposes, such as to check the weather, determine the current stage of a river, and identify the magnitude and location of an earthquake. In addition to providing a snapshot of current conditions, long-term data-collection networks provide a means for identifying trends and for calibrating computer simulation models that are used to estimate conditions at unmonitored sites and to predict future conditions. As such, monitoring networks are integral to our understanding of the past, current, and future effects of energy production on water and ecosystem resources.

Data-collection networks exist at State, regional, and national levels in the United States. The national network most familiar to people is probably the National Weather Service (*http://www.weather.gov/*), a weather station network supported by the National Oceanic and Atmospheric Administration that provides precipitation, temperature, and other data from thousands of locations across the United States on a daily and sometimes real-time basis. This weather information is used by Americans who are curious about the day's weather, by forecasters who predict weather patterns for coming days, and by climatologists who predict long-term climate trends. An example of a regional scale network is SNOTEL (*http://www.wcc.nrcs.usda.gov/snow/*), a network supported by the National Resources Conservation Service for collecting data on snowpack and climatological parameters at over 600 sites in 13 western States. The original intent of the SNOTEL network was to provide data for estimating rates and volumes of snowmelt that could be used in decision-support models for optimizing storage and release from surface-water reservoirs. The data are still used for that purpose, but the data are also widely used for climate research. On a State level, Montana has a network of monitoring wells for assessing changes in groundwater levels related to coal mining and development of coalbed natural gas (Meredith and others, 2012). Data from networks such as these provide valuable insight on many water-energy issues; however, if data collection is too widely spread in space or time, localized effects of energy production may go undetected. Regardless of network extent, the integrity of any data can be guaranteed only if quality assurance and control protocols are in place and followed.

Hydrologic, ecosystem, and seismic data-collection networks can be expensive to operate and maintain, and often the benefits that they provide are not fully recognized. For these reasons, funding for these networks is often reduced in times of fiscal austerity. Such measures are unfortunate because monitoring networks serve a variety of interests. For example, water and ecosystem managers, agricultural planners, industrialists, environmentalists, and outdoor enthusiasts are among those who rely on consistent and available hydrologic data. Recently, common interests in water availability and quality have brought together diverse groups to support expanded monitoring in some regions of the United States in order to assess the potential effects of energy development. One such region is the Piceance Basin in northwestern Colorado (see Box O—Piceance Basin Water-Quality Data Repository).

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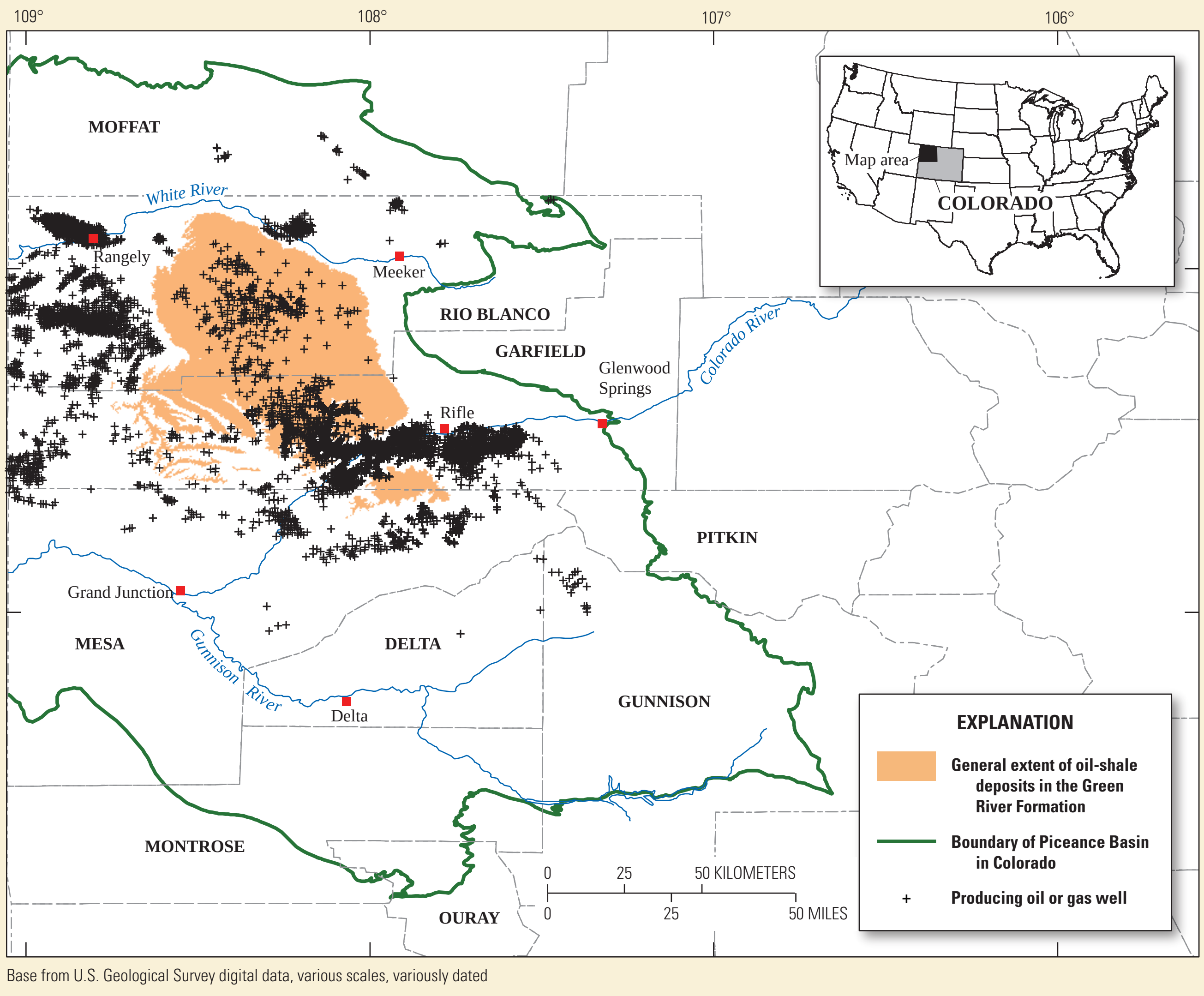
O Piceance Basin Water-Quality Data Repository—A Tool for Water-Resource Monitoring Related to Energy Development

The Piceance Basin occupies about 25,000 km^2 in northwestern Colorado (fig. O–1) and contains vast energy resources. Sediments of the Mesaverde Group and Wasatch Formation contain about 133 billion m^3 of undiscovered natural gas (U.S. Geological Survey, 2003). Oil shale of the overlying Green River Formation contains an estimated 240 trillion L of oil (Johnson and others, 2009). Commercial production of natural gas in the basin began more than 50 years ago. As of 2012, there were more than 12,000 producing oil and gas wells in the basin. Many of the gas wells are hydraulically fractured to increase gas production, which can require several million liters of water per well. Production of oil from shale is still largely a research effort on the part of energy companies because the oil shale was never buried deeply enough to generate oil; thus, the temperature of the shale must be raised in order to produce oil. Estimates of water consumption for oil shale development generally range from about 1 to 12 liters of water per liter of oil produced; however, these estimates are not well constrained because methods of production are still being developed (U.S. Government Accountability Office, 2011b). Nevertheless, these water-use estimates represent substantial quantities of water given the large volume of in-place oil.

Most of the basin has a semiarid climate, so water resources are limited. The primary sources of freshwater include major rivers such as the Colorado, Gunnison, and White, as well as bedrock aquifers and alluvial deposits along the rivers. Surface-water and groundwater resources in the



Base from U.S. Geological Survey digital data, various scales, variously dated

Figure O–1. Location of producing oil and gas wells, oil shale deposits, and major rivers in the Piceance Basin, Colorado.

basin support many uses in addition to energy development, including agriculture, urban and rural communities, industry, and terrestrial and aquatic ecosystems (Thomas and McMahon, 2012). There is concern that the availability and quality of water for these other uses could be affected as large-scale energy development continues.

A water task force consisting of citizens; local, State, and Federal governmental agencies; and energy companies collectively identified the need for a common repository for water-quality data collected by numerous monitoring programs that operate in the basin. The U.S. Geological Survey, in cooperation with more than two dozen partners, created a public, Web-accessible common data repository that combines water-quality data from industry, local, State, Federal, and other sources (*http://rmgsc.cr.usgs.gov/asp-bin/cwqdr/Piceance/index.shtml*). The quality and completeness of the incoming data are reviewed, documented, and stored into a single uniform format. All available water-quality data have been evaluated to assess the current conditions of the region's water resources (Thomas and others, 2013: Thomas and McMahon, 2012). Results of the assessment facilitate the development of regional monitoring strategies to fill identified data gaps and minimize redundancies in current and future water-resource monitoring. This common data repository for the Piceance Basin provides a valuable contribution to the planning, monitoring, conservation, and management of water resources as energy development continues.

Above: U.S. Geological Survey streamgage on the White River below Meeker, Colorado.

Right: Flaring of natural gas in the Piceance Basin.

Available Freshwater

Priorities for Assessing Freshwater Availability

- Develop methods for conducting a water census.
- Reduce uncertainty in watershed water-budget calculations.
- Establish a national groundwater monitoring network.
- Expand monitoring of surface water, groundwater, and water quality in areas of future energy development.
- Integrate models of water quality and ecosystem health.

As competition for water grows, the need for information and tools to aid water-resource managers also grows, yet a comprehensive assessment of water availability in the United States has not been made in more than 40 years (U.S. General Accounting Office, 2003). The U.S. Water Resources Council published a rudimentary national assessment in 1968 (U.S. Water Resources Council, 1968) and the more comprehensive Second National Water Assessment 10 years later (U.S. Water Resources Council, 1978).

A national assessment of water availability is a complex undertaking. At the time of the previous national assessments, water availability was viewed in comparatively simple terms. These early assessments focused largely on basic statistics about the quantities of water available for various human uses. Since then, competition for water resources has increased and more importance has been attached to the availability of water for environmental and ecosystem uses, in addition to human use. Likewise, concerns have grown about groundwater depletion, streamflow alteration, climate change and variability, and water-quality impairment. Awareness of the connectivity of surface water and groundwater and the links between water availability and the use of energy and other natural resources has also increased.

The Secure Water Act, Subtitle F of the Omnibus Public Land Management Act of 2009 (Public Law 111-11; passed into law on March 30, 2009), helps address the need for more information. Section 9508 of the Act calls for the establishment of a "national water availability and use assessment program," or a "national water census" (Alley and others, 2013). According to the Act, the water census should

- provide a more accurate assessment of the status of the water resources of the United States;
- assist in the determination of the quantity of water that is available for beneficial uses;
- assist in the determination of the quality of the water resources of the United States;
- identify long-term trends in water availability;
- use each long-term trend to provide a more accurate assessment of the change in the availability of water in the United States; and
- develop the basis for an improved ability to forecast the availability of water for future economic, energy-production, and environmental uses.

The water census is intended to synthesize information at the regional and national scales and to report this information in a way that is useful to States and others responsible for water management and natural-resource issues. The water census is a collaborative effort involving the U.S. Geological Survey, the U.S. Bureau of Reclamation, other Federal and State agencies, universities, and additional organizations. Information provided by the census can be aggregated with socioeconomic information, such as data on food and energy production, to maximize its utility. Design and development of the water census is coordinated through the Federal Advisory Committee on Water Information (*http://acwi.gov/*).

Much of the information in a national assessment of water availability pertains to water budgets for watersheds (fig. 32) and aquifers (Box B—Water Availability and Use in the United States). Water budgets account for the inputs to, outputs from, and changes in the amount of water stored in the various components of the water cycle over a fixed volume (such as a watershed) and a fixed time interval (such as a year). The water-budget components of most interest are precipitation, evapotranspiration, change in storage, and flow into and out of the watershed or aquifer. A long-term goal of the national water census is to provide measurements or estimates of these components on a monthly basis for all watersheds at the 12-digit hydrologic unit code scale (average drainage area of about 95 km^2) (Alley and others, 2013). A dedicated hydrologic data-collection network is a key element in efforts to achieve this goal, but given current measurement technologies, it is not practical to measure every water-budget component at each of these watersheds. Instead, hydrologic simulation models can be used to estimate components for many watersheds. Improvements in models and methods for collecting data, such as with satellite remote sensing, can enhance current capabilities.

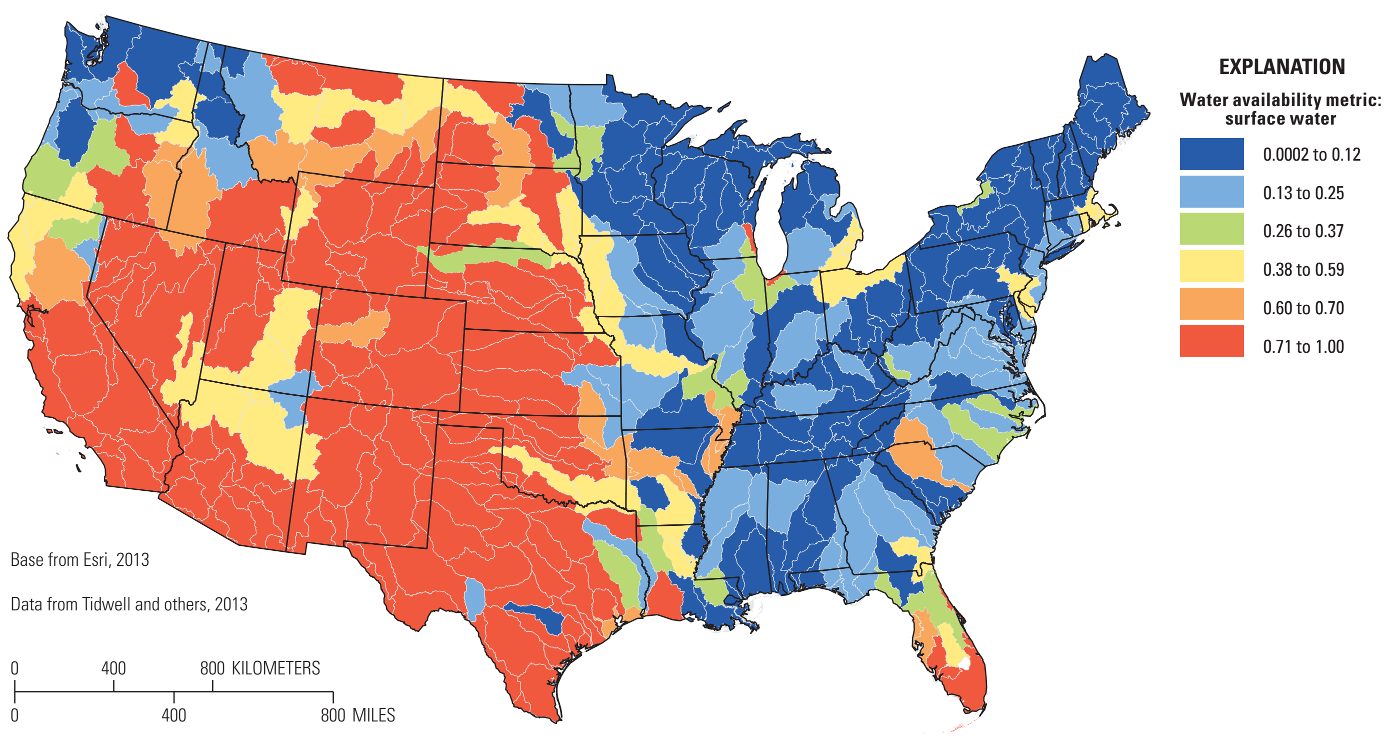


Figure 32. Surface-water availability as defined by a metric based on measured streamflow and current water use. High values (greater than 0.7) (in red) indicate areas of limited surface water availability. Water availability in this study was determined for watersheds at the 6-digit hydrologic unit code scale (average drainage area of about 22,000 square kilometers) in order to assess water availability for new thermoelectric power plants. (Tidwell and others, 2012, 2013)

Uncertainty in water availability assessments is also a concern. Uncertainty is inherent in data collection, data interpretation, and in application of hydrologic models. Water management options can be evaluated more effectively if the uncertainty levels in all water-budget calculations are known. Development of improved methods for quantifying and reducing uncertainty in water-budget analyses of watersheds would be highly beneficial for a national water census.

Water Quantity Monitoring

The U.S. Geological Survey, in collaboration with over 850 Federal, State, and local agencies maintains the National Streamflow Information Program (*http://water.usgs.gov/nsip*), a surface-water gaging network that monitors streamflow at more than 8,000 sites nationwide. The streamflow information is vital for a number of purposes—assessing water availability, predicting the occurrence of and assessing the extent of floods and droughts, monitoring aquatic ecosystem habitat, designing bridges and conveyance structures, and identifying trends in streamflow that might be natural or that might result from human activity. Many of these purposes are linked to the water-energy nexus. Data from streamflow monitoring is needed to determine water availability for current and future energy production activities, such as cooling at thermoelectric power plants and fuel extraction, growth, and processing; to control withdrawals of surface water so as to preserve sufficient surface-water flow to support aquatic habitats; and to calibrate models used to predict the occurrence and severity of droughts, which can lead to reductions in the availability of power-plant cooling water. The accuracy of any predictions usually improves as the length of the period of data collection increases. Streamflow records also can be used to evaluate the effects of land-use changes related to energy production, such as those caused by mountaintop mining and the conversion of native grasslands to row crops for biofuels production.

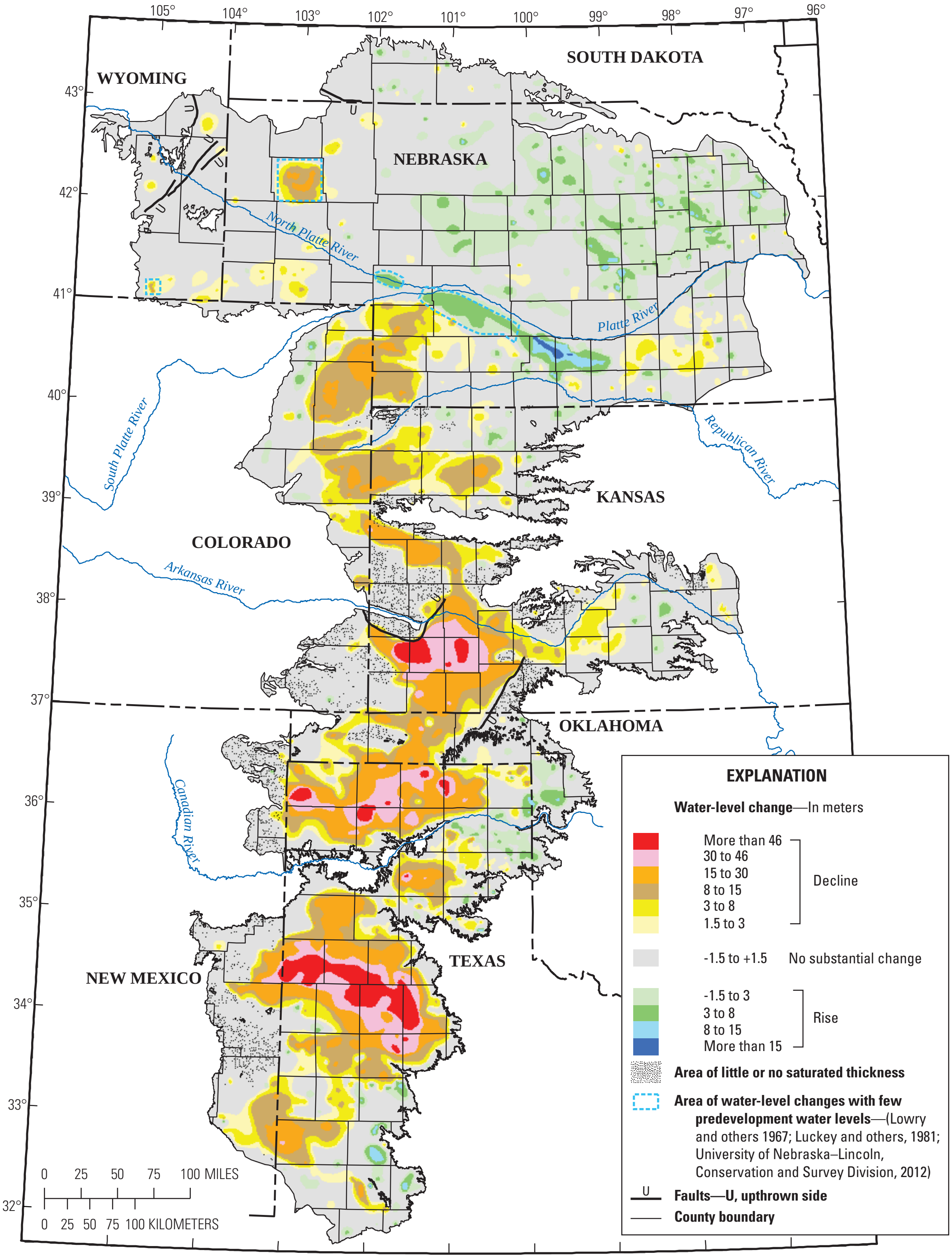
Groundwater levels are measured at many thousands of observation wells across the United States. Measurements are made manually, at weekly to annual frequencies, and by automated continuous recorders. These wells belong to networks maintained by local, State, regional, or Federal agencies. Currently, there is no national groundwater monitoring network within the United States. Through the Groundwater Watch Program (*http://groundwaterwatch.usgs.gov/*), the U.S. Geological Survey maintains a database of groundwater levels for approximately 850,000 wells, but only about 20,000 of those wells had water-level measurements in 2013, and even fewer wells (about 2,500) had daily or more frequent measurements. Measurements of groundwater levels are useful for assessing water availability and identifying natural trends and those related to human activities (fig. 33). In regard to the water-energy nexus, groundwater information is important for assessing water availability for energy development and for monitoring effects of energy operations such as coal mining, extraction of coalbed natural gas, irrigation of biofuel feedstock crops, and subsurface injection of wastewater and carbon dioxide.

Groundwater levels typically change slowly, so years to decades of water-level measurements are required to evaluate the long-term effects of aquifer development, land-use change, and climate change. Ideally, a record of groundwater-level measurements would encompass the period between the natural state and the developed state of aquifer systems. A comprehensive water-level monitoring program would consider important aquifers within the United States and the way that they are affected by current and future groundwater development, major areas of groundwater recharge, and links with surface-water and water-quality monitoring. The Advisory Committee on Water Information has proposed the establishment of a national groundwater monitoring network in the United States (Subcommittee on Ground Water, 2013).

Water Quality Monitoring

The availability of water is determined by water quality as well as water quantity. High concentrations of many naturally occurring and synthetic substances can limit the suitability of water for some uses. The U.S. Environmental Protection Agency (2009) estimated that more than one-third of streams and rivers in the United States are impaired or polluted. Energy production is just one of many human activities that can lead to the contamination of water resources.

Water quality monitoring supports multiple goals, such as safeguarding human and ecosystem health, assessing availability of water for specific uses, identifying causes of water contamination, and evaluating strategies for remediation of that contamination. With respect to the water-energy nexus, water-quality information is useful for determining whether or not water from a particular source can be used for a specific application, such as irrigation or cooling. The information is also useful for identifying the occurrence, extent, and possible cause of contamination generated by energy-related operations. The water quality of surface waters and groundwater is monitored through two approaches: collection and analysis of discrete water samples and continuous in-place monitoring (for some parameters). Discrete samples can be analyzed in the laboratory for hundreds of physical, chemical, and biological properties. Continuous recorders, on the other hand, are capable of measuring only a handful of properties (such as temperature, specific conductance, pH, dissolved oxygen concentration, and nitrate concentration), but data from these recorders can be obtained at frequencies as high as every minute. Both of these approaches provide useful information for determining the current state of water quality and for identifying trends over time. Data from continuous recorders and measured streamflow can be used to estimate concentrations and loads for unmeasured constituents based on regression equations developed for individual sites (see, for example, the real-time water quality data available for Kansas: *http://nrtwq.usgs.gov/ks/*).



Base from U.S. Geological Survey digital data, 2001, 1:2,000,000
Albers Equal-Area Conic projection, standard parallels 29° 30' and 45° 30', central meridan -101°
North American Datum of 1983 (NAD 83)

Aquifer boundary from Qi (2010); areas of little or no saturated thickness and faults from Gutentag and others (1984) and Cederstrand and Becker (1999a, 1999b)

Figure 33. Water-level changes in the High Plains aquifer, from predevelopment to 2011 (McGuire, 2013). The High Plains Regional Groundwater Level Monitoring Network includes about 9,000 wells and is perhaps the largest regional network in the United States. Water levels in wells in the network are measured annually, predominantly by local and State agencies. (U.S. Geological Survey, 2014b)

Water-quality monitoring networks usually are operated at local and State levels. The collected data, which include biological and chemical analyses of water samples and fish tissue, often are stored in the U.S. Environmental Protection Agency STORET (Storage and Retrieval) database. Biennial assessments are conducted by each State using these data and additional information obtained from predictive models and surveys of land use and ecosystems (U.S. Environmental Protection Agency, 2013c). In collaboration with other agencies, the U.S. Geological Survey operates continuous water-quality recorders at about 1,700 sites across the country; in addition, discrete samples are collected and analyzed at many sites under programs such as the National Water-Quality Assessment (NAWQA) Program (*http://water.usgs.gov/nawqa/*) and the National Stream Quality Accounting Network (*http://water.usgs.gov/nasqan*). The NAWQA program supports long-term monitoring of water quality and aquatic ecosystem health, research on causes and effects of water contamination, and analyses of trends. Water quality data in U.S. Environmental Protection Agency, U.S. Geological Survey, and U.S. Department of Agriculture databases can be accessed through the Water Quality Portal (*http://www.waterquality-data.us/*).

Models are important tools for characterizing water quality and ecosystem health. Because of practical considerations, water quality can be directly monitored at only a limited number of sites, but models can be used to gain an understanding of water quality at unmonitored sites. Models are also useful for identifying factors that control contaminant transport and for evaluating options for remediation of contaminated sites. Water quality studies would benefit from development and application of models that are capable of integrating information on water movement, chemistry, biology, habitat, and land and water use to provide improved predictions of the effects of natural phenomena and human activities on water quality and ecosystem health.

Collection and analysis of discrete water-quality samples can be expensive, which could place limits on the number of sites and frequency of sampling in a network. Water temperature, however, can be continuously monitored at a relatively low cost. Water-temperature data are important for assessing rates of climate change and the health of aquatic ecosystems. They are also important for thermoelectric power plants; withdrawals for cooling may be restricted if water temperatures exceed regulatory limits. A number of networks have been established in parts of the United States specifically to monitor stream temperatures (U.S. Forest Service, 2014).

Determining the effects of human activities on the water quality of any hydrologic system requires insight on the water quality of that system prior to the time at which human activities were initiated. Baseline, or background, water-quality data can provide that insight, but unfortunately such data are scarce for shallow aquifers in many regions of oil and gas development. Moreover, existing wells with background data are not always suitable for monitoring effects of energy development because wells may not be located proximate to energy operations or the period of data collection may not be long enough to detect contamination, should it occur (McMahon and others, 2013). Understanding the hydrologic framework in which wells are located is important for evaluating the usefulness of existing wells as monitoring points.

Water Use

Priorities for Monitoring Water Use

- Develop improved methods for measuring or estimating water withdrawal and consumption for energy use, especially by hydroelectricity generation and biofuels production.

The use of water by humans is an important component of the global water cycle. Understanding the relation between water use and the water cycle can shed light on how human activities affect climate and how both human activities and variations in climate affect water availability. As such, water-use information is important in many fields. In particular, information on rates of water withdrawal, conveyance, consumptive use, and return flow are vital to understanding the links between water availability and energy production. Regular assessments of water use provide trend information that can support planning for future water needs. Since 1950, the U.S. Geological Survey has compiled assessments of water use in 5-year intervals and published results in a series of reports entitled “Estimated Use of Water in the United States.” These assessments are collaborative efforts involving all 50 States and multiple Federal agencies. Water-use data are provided for eight distinct categories: public supply, domestic supply, irrigation, livestock, industrial, aquaculture, mining, and thermoelectric power. The most recent water use report covered years 2006–2010 (Maupin and others, 2014).

Thermoelectric power represents about 45 percent of water withdrawals in the United States (Maupin and others, 2014). Nearly all of the water withdrawn for this use is returned to a surface-water body and is readily available for other uses. For the 2000, 2005, and 2010 water-use reports, consumptive water use by thermoelectric power plants was not reported. Future plans call for incorporating consumptive use data into the national water-use database maintained by the U.S. Geological Survey (*http://waterdata.usgs.gov/nwis/wu*) (M.A. Maupin, U.S. Geological Survey, written commun., 2014). Methods for estimating power-plant water consumption can be improved by incorporating information on plant characteristics, power generation, fuel use, type of cooling system, and climate. Better techniques for estimating consumptive use of power plants will account for the evaporation caused by the increased temperature of water used for cooling after it is returned to a stream or reservoir (Diehl and others, 2013; Diehl and Harris, 2014).

Estimation of water consumption rates for generating hydroelectric power and for growing biofuels poses unique problems. The amount of water that evaporates annually from reservoirs that feed hydroelectric plants may be larger than the total amount of water consumed for all other electricity-generating operations in the United States, even though hydroelectricity represents only 7 percent of all generated electricity (table 4). However, uncertainty is inherent in estimates of water consumption at hydroelectric plants because evaporation rates are difficult to accurately determine and few studies have been conducted on reservoirs associated with these plants. Even if accurate estimates of reservoir evaporation were available, the question of whether all of the evaporation should be assigned to the generation of electricity needs to be addressed (Bakken and others, 2013). Dams and reservoirs are constructed for multiple purposes; portions of the evaporated water might more correctly be assigned to uses such as water supply, recreation, or flood control. The development and application of a uniform method for allocating water consumption from reservoirs would help to reduce the uncertainty associated with water consumption by hydroelectric plants. With regard to biofuels, water use is associated primarily with irrigation. Estimates are available for the amount of irrigated acreage of corn and soybean crops in the United States, but the percentages of these irrigated crops that are processed into bioethanol or biodiesel are not known. This uncertainty limits our ability to accurately determine overall water consumption rates for the transportation sector.

Seminoe Dam and power plant, Wyoming.

Ecosystems

Priorities for Assessing Monitoring Ecosystems

- Standardize methods for assessing ecosystem services.
- Adapt monitoring programs to include information that can be used to quantify and value ecosystem services.
- Develop decision-support tools to allow resource managers to include ecosystem services in cost-benefit analyses of energy development scenarios.

Ecosystems are communities of plants, animals, and microbes that live and interact with nonliving components such as water, air, and soil minerals. They range in size from a microscopic area to a puddle of water to an ocean or a continent. The Earth itself can be viewed as an ecosystem. The structures and processes of ecosystems provide a number of beneficial services to humans, including purification of air and water, mitigation of droughts and floods, generation and preservation of soils and renewal of their fertility, detoxification and decomposition of wastes, pollination of crops and natural vegetation, dispersal of seeds, cycling and movement of nutrients, and control of the vast majority of potential agricultural pests (Daily, 1997). Additional services contribute to human enjoyment, such as the aesthetic qualities provided by forests and water bodies as well as recreational and cultural opportunities. The health of ecosystems and the benefits they provide, however, are affected by human activities. Energy and water development can result in changes in land use, water quantity and quality, and air quality. These changes can adversely affect ecosystems.

The wide range in spatial scales associated with ecosystems has led to a variety of approaches for the assessment and monitoring of their health. There are no national-level ecosystem monitoring networks, and there are no standard metrics for measuring ecosystem health, but there are a number of smaller programs that provide important information on ecosystems. Within the United States, each State has a wildlife management program, with the Federal government providing oversight for the management of endangered species (U.S. Fish and Wildlife Service, 2014). Surveys for fish, big game, and waterfowl are conducted regularly to support management programs that include fishing and hunting. For aquatic ecosystems, water quality analyses, as described previously, provide important information on ecosystem health. Within the Department of the Interior, two agencies have established Inventory and Monitoring programs to monitor ecosystems on lands they manage: the National Park Service (*https://science.nature.nps.gov/im/*) and the U.S. Fish and Wildlife Service (*http://www.fws.gov/Refuges/NaturalResourcePC/IandM/*). These programs were set up to assess the effects of climate change and land-use change on ecosystems. On the national level, the National Ecological Observation Network (NEON, *http://www.neoninc.org*) is currently (2014) being established with funding from the National Science Foundation. The goal of NEON is to monitor the causes and effects of climate change, land-use change, and invasive species on ecosystems in the United States. Collection of atmospheric, soil, organismal, and aquatic data is planned at 60 terrestrial and 36 aquatic sites across the United States.

A desert spring offers services such as water for humans, vegetation, and local and migratory wildlife. Cultural and aesthetic aspects of such features are cherished by many humans. Lack of consistent methodology inhibits our ability to quantify the amount of services provided by ecosystems and to determine the value of those services.

The Wyoming Landscape Conservation Initiative (WLCI, *http://www.wlci.gov/*) is a unique endeavor supported by the U.S. Bureau of Land Management and several Federal, State, and local agencies. The WLCI is a long-term science based effort to assess and enhance aquatic habitats while facilitating responsible energy and agricultural development in a large area of southwestern Wyoming (fig. 34). The WCLI addresses management needs identified by its partners through a program of monitoring and research. Approaches for addressing those needs include developing conceptual models for understanding ecosystem function, identifying key drivers of change affecting WLCI ecosystems, and conducting scientific monitoring and experimental studies to better understand ecosystems processes, cumulative effects of change, and the effectiveness of habitat treatments (Bowen and others, 2009).

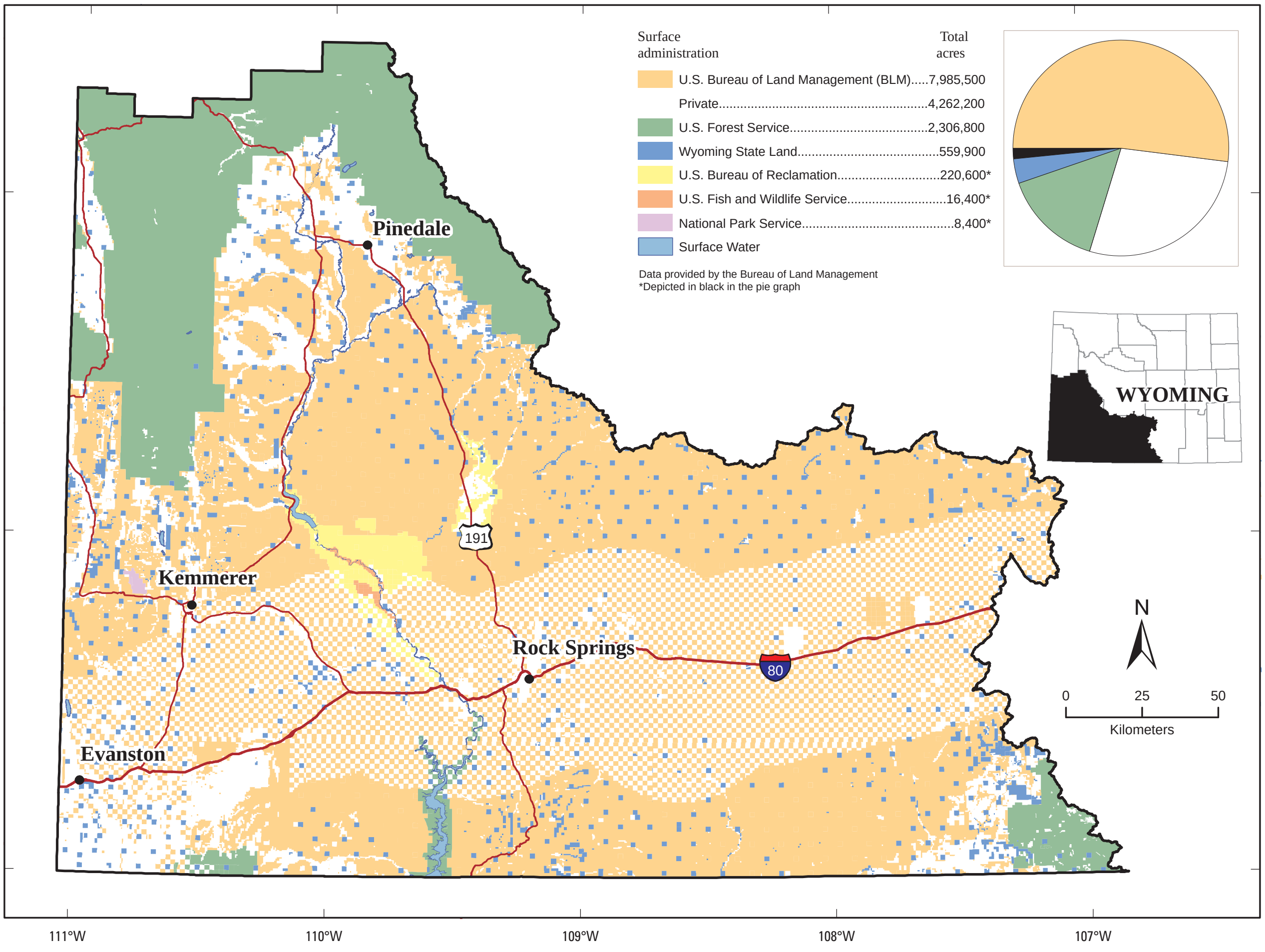


Figure 34. The Wyoming Landscape Initiative area, including surface jurisdiction. (Bowen and others, 2009)

Data obtained from programs such as these and from site- and ecosystem-specific assessments can be useful for assessing the effect of energy development. However, the lack of a consistent, standardized method for measuring ecosystem services hinders efforts to develop a universally accepted accounting system (Boyd and Banzhaf, 2006) in which, for example, the value of oil or natural gas extracted at a particular location could be compared with the value of the ecosystem services that were lost as a result of that extraction. Haines and others (2013) present a framework that can be used to generate quantitative assessments of the effects of fossil-fuel extraction on ecosystems. Ideally, new tools will be developed to determine equivalent economic values of affected ecosystem services in a consistent and unbiased approach, which could lead to the inclusion of cost-benefit analyses into decision-support software and, in turn, would allow for direct comparison of environmental costs of different development schemes (Darius Semmens, U.S. Geological Survey, written commun., 2014). Resource managers could use these comparisons to select development scenarios or management strategies to reduce adverse effects on ecosystem services.

Saline Groundwater Availability

Priorities for Assessing Saline Groundwater Availability

- Determine the distribution and physical and geochemical properties of saline aquifers.
- Improve our understanding of the connection between freshwater and saline aquifers.

Concern about the sustainability of freshwater supplies has fostered interest in the use of nontraditional water sources. Saline groundwater (water with total dissolved solids concentration greater than 1,000 mg/L) is increasingly being viewed as a valuable resource that can be used in place of freshwater for many purposes. Desalination, for example, offers the possibility of producing drinking water from saline groundwater or seawater. In 2007, the city of El Paso, Texas, brought on line the largest inland desalination plant in the United States, producing about 100 million L of water daily (El Paso Water Utilities, 2007). Desalination is an energy-intensive process; however, treatment to the level required by drinking-water standards is not always necessary. With minimal or no treatment, saline water can be used for a number of energy-related purposes, including drilling and hydraulic fracturing. In addition to being tapped as a source of groundwater, saline aquifer systems are widely used for the disposal of wastewater. The El Paso desalination plant disposes of the liquid concentrate produced by the reverse osmosis process by deep well injection. Information on the locations and characteristics of saline aquifer systems can promote more efficient and environmentally sound operations.

Areas of aquifer systems containing saline water commonly are connected hydraulically to areas of the same system that contain freshwater. Thus, development of one resource may affect the other. Little information is available on the hydrogeology of the parts of most aquifers that contain saline water (fig. 35) because of limited interest in saline groundwater in the past. Improved understanding of the hydrogeology of these systems can provide insight on the volumes of water that could be extracted, the rates at which wastewater and carbon dioxide could be injected, and the potential for induced seismic activity and contamination of freshwater aquifers from injection operations.

Geochemical data on saline groundwater resources are also scarce. The chemistry of saline water can affect the usability of the water. Saline groundwater can contain high concentrations of naturally occurring constituents, such as arsenic and radioactivity, that can limit the allowable uses of the water. Water chemistry must also be considered in design and planning of wastewater injection operations; incompatible chemistries of native formation water and injected waters can lead to unintended reactions such as precipitation of solids that can reduce aquifer permeability and clog well screens (Kharaka and others, 1997). An improved knowledge base can better define the distribution and physical and chemical characteristics of saline aquifer systems and groundwater and,

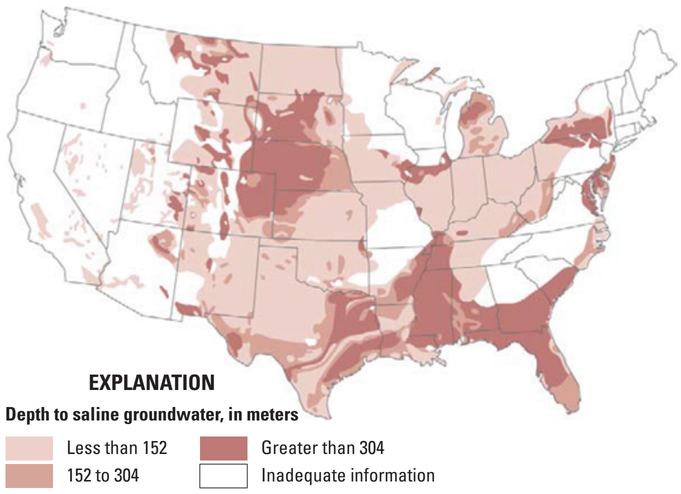


Figure 35. Generalized map of the depth to saline groundwater for the conterminous United States. This map provides a preliminary perspective on the location of saline groundwater resources, but it contains limited information about critical factors required to understand the development potential of the resources, such as aquifer permeability and well yields. (Modified from Feth and others, 1965)

in so doing, support more accurate predictions of the effects of saline-water extraction and wastewater and carbon dioxide injection on the aquifer system and the environment. In addition to helping guide development and protection of resources, this information can provide a scientific basis for regulatory and policy issues.

Fossil Fuels and Uranium

Priorities for Assessing Fuel Resources

- Update assessments when new energy-development techniques emerge.
- Develop improved assessment techniques.
- Integrate water and ecosystem assessments into energy resource assessments.

The United States accounts for about 18 percent of worldwide energy consumption (International Energy Agency, 2012a). Knowledge about our domestic energy potential from fossil-fuel and uranium sources is important for planning for future energy development. For example, rapid expansion of shale gas and tight oil over the past decade has dramatically affected the Nation's energy outlook. Producing fundamental data on the quantity and location of undiscovered energy resources, such as oil, natural gas, and coal, is a core activity of the U.S. Geological Survey (*http://energy.usgs.gov/*). This information is conveyed in the form of assessments of undiscovered, technically recoverable energy resources, that is, resources that are yet to be discovered but, if present, can be extracted using existing technology (see, for example, Scott and Luppens, 2013). The assessment methods are probabilistic to take into account uncertainty; they provide estimates of upper and lower bounds around a median value. The assessment data, when combined with data generated by the Bureau of Ocean Energy Management (*http://www.boem.gov*) and the Energy Information Administration (*http://www.eia.gov*), provide a broad perspective of available energy resources of the United States.

As new technologies evolve and additional information becomes available, assessments of energy resources need to be updated. In some cases, revised assessments can have a significant effect on resource development. In the wake of enhanced technologies such as hydraulic fracturing and directional drilling, the assessed undiscovered, technically recoverable oil resources of the Bakken-Lodgepole total petroleum system (fig. E–1) have increased from 24 billion L in 1995 to 477–684 billion L in 2008 (Pollastro and others, 2008) to 0.8–1.8 trillion L of oil in 2012 (Gaswirth and others, 2013). This system is currently the largest assessed, undiscovered unconventional oil resource in the United States. Assessment methods themselves undergo periodic revision to reflect improvements in estimation techniques and additional information that may become available. The methodology used by the U.S. Geological Survey for the assessment of unconventional hydrocarbon resources was revised in 2005 and again in 2010 (Charpentier and Cook, 2010).

Additional beneficial uses of energy assessments should be explored. Many questions related to development of unconventional oil and natural gas resources remain unanswered: How much water is needed for drilling and wellbore stimulation? How much fresh and saline water is currently being used for these purposes? What are the impediments to using recycled or produced water for these purposes? Linking energy assessments to assessments of water, ecosystems, and other resources can be beneficial in a number of ways. The creation of a methodology for assessing the lifecycle water use for the development of unconventional oil and gas resources would benefit energy, water-resource, and ecosystem managers, as well as energy and water developers and water users. A better understanding of water use on a well-by-well basis would lead to improved estimates of water use at the regional and national scales. A consistent accounting of life-cycle water use would facilitate cooperative planning of energy and water development activities and thus help to avert conflicts among different water users (Haines and others, 2014; Nicot and others, 2014).

Geothermal Resources

Priorities for Assessing Geothermal Resources

- Identify untapped traditional hydrothermal fields.
- Develop a fundamental understanding of the way in which geothermal systems function, including water and energy balances and their relation to seismic activity.
- Identify favorable sites for enhanced geothermal system power plants and determine the water requirements and potential seismic hazards.

The geothermal systems that currently provide electricity to the power grid are the systems that were the easiest to discover and develop. Other hydrothermal fields, whose surface expression is less obvious, might prove to be good sources for electricity generation. Undiscovered moderate- to high-temperature geothermal resources could exist in regions such as the Basin and Range Province, the Cascade Range, the Salton Trough, and the Rio Grande Rift, as well as deep sedimentary basins (Duffield and Sass, 2003). Undiscovered traditional hydrothermal fields in the United States could be capable of producing 30,000 MW of electricity, or about 15 times the generating capacity of currently operating geothermal plants (Williams and others, 2008). A program of targeted geophysical studies and drilling would help identify these potential sites.

Harnessing geothermal energy relies on the presence of high subsurface temperatures, a geofluid, and a highly permeable structure in the subsurface that allows for rapid movement of the geofluid. Many areas of the United States have subsurface temperatures that are sufficiently high to allow geothermal development, but because of low permeability in these areas, geofluids cannot be rapidly circulated. Enhanced geothermal systems have been proposed, however, whereby the permeability of the subsurface would be increased (perhaps by hydraulic fracturing) to allow rapid circulation of geofluids. The potential for enhanced geothermal systems in the United States is substantial. Enhanced systems could be capable of producing up to 500,000 MW of electricity, equivalent to about one half of the entire electricity-generating capacity of the United States (Williams and others, 2008). Enhanced geothermal systems are simple in concept, but development of these systems on a commercial scale has proved to be challenging. The 1.7-MW Desert Peak 2 plant in Nevada, which came on line in April of 2013, is the first commercial enhanced geothermal system power plant in the United States (U.S. Department of Energy, 2013a).

In addition to its use in the production of electricity, geothermal energy can be used directly to heat buildings, streets, and sidewalks. Energy from a geothermal reservoir that lies at a depth of about 900 m beneath Boise, Idaho, is used to heat more than 400 buildings in the city, including the State Capitol Building. Geothermal heat pumps are used in many areas of the United States to supplement both heating and cooling systems for residential, commercial, and industrial buildings.

Operational water requirements for enhanced geothermal resources are largely unknown and will depend on the cooling methods that are employed. The requirements could be similar to those for traditional binary geothermal systems, but with additional water required during initial development of the site to enhance permeability.

Planning and development of future enhanced geothermal systems can benefit from a wide range of research. Identification of potential power plant sites relies on continued assessments of geothermal resources and development of more sophisticated assessment methods. Accurate estimates of water requirements for developing these systems as well as local assessments of available water are also critical factors for siting new plants. Beyond that, improved techniques for enhancing the permeability of host rocks could open up additional areas for potential development of enhanced geothermal systems.

Management of both traditional and enhanced geothermal systems can benefit from research to better understand the fundamental nature of geothermal reservoirs and the way in which they function. An understanding of the geofluid balance, the energy balance, and the geomechanical features of a reservoir (such as structure, lithology, permeability, fault and fracture characteristics, and stress) can lead to improved efficiency of operation as well as an extended life for the reservoir. Measurements of seismic activity, when used in conjunction with this information could substantially enhance our understanding of the relation between plant operation and induced seismic activity and, in so doing, lead to safer plant operation.

Induced Seismicity

Priorities for Studying Induced Seismicity

- Expand seismic monitoring in areas of energy development.
- Improve our understanding of factors that contribute to induced seismic activity.

Earthquakes occur naturally. They can also be induced by a number of human activities including nuclear-weapons testing, reservoir construction, and energy-related activities such as wastewater and carbon dioxide injection and development of geothermal systems. Ascertaining whether human activity is the cause of an earthquake can be difficult. It appears likely, however, that induced seismicity from energy operations has contributed to the trend, since 2001, of increasing numbers of earthquakes of magnitude 3 or higher in the central and eastern United States (fig. 36) (Ellsworth, 2013).

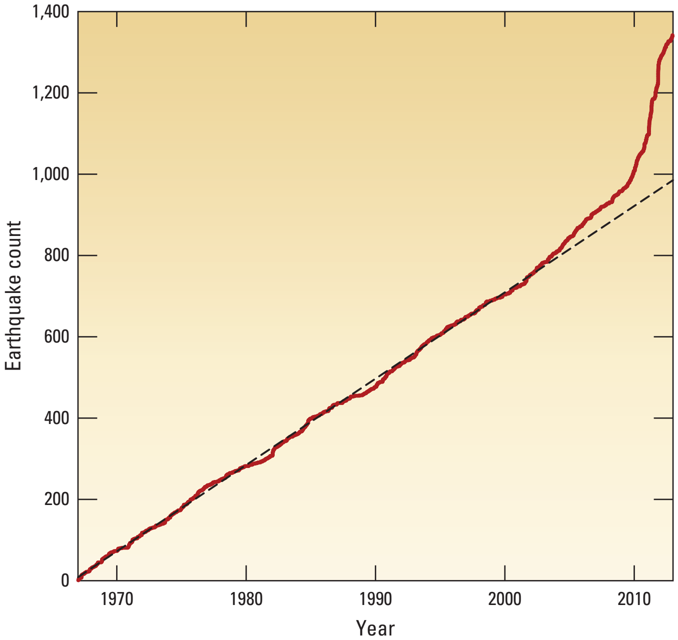


Figure 36. Cumulative count of earthquakes with magnitude (M) greater than 3 in the central and eastern United States, 1967–2012. The dashed line corresponds to the long-term rate of 21.2 earthquakes per year. (Ellsworth, 2013)

Dedicated networks of seismometers exist across the United States and have been operational for many years. These networks serve two primary purposes: monitoring earthquake and volcanic activity and conducting research on Earth's fundamental geological structure and processes. The Advanced National Seismic System (ANSS, *http://earthquake.usgs.gov/monitoring/anss/*) is a partnership of the U.S. Geological Survey, academia, other government agencies, and industry that monitors seismic activity across the United States. Since its inception in 2000, funding has provided for the installation of more than 700 fixed-position stations for collecting high-quality seismic data to serve the needs of the emergency management and response, engineering, and scientific communities in regard to earthquake and volcanic activity. The Incorporated Research Institutions for Seismology (IRIS) supports USArray (*http://www.usarray.org/*), which is another array of transportable seismometers; these sensors are deployed for periods of 1 to 2 years to provide more detailed spatial coverage than can be obtained with the ANSS network. Because of the wide spacing between sensors in the networks and the fact that earthquakes of magnitudes less than 3 are typically not reported (Ellsworth, 2013), these networks are not ideal for detecting seismic activity induced by energy operations. However, because of the fortuitous deployment of seismometers in the USArray network, researchers recently were able to link the magnitude, timing, and location of earthquakes in parts of Oklahoma with operations at nearby subsurface injection wells, thereby suggesting that wastewater injection triggered the earthquakes (Keranen and others, 2013).

Enhanced monitoring networks (where earthquakes of magnitudes less than 3 can be monitored) in the vicinity of energy operations would be beneficial for safety, regulation, and research purposes; more refined data would facilitate improved procedures for injection of wastewater and management of geothermal systems. For example, rates of wastewater injection might be reduced if nearby seismic activity reaches a certain magnitude. Such "traffic light" systems have been in use at a number of facilities for many years (Ellsworth, 2013). When combined with additional information on hydrogeology, stress and pressure conditions, withdrawal and injection rates and volumes, and presence and characteristics of nearby faults, enhanced monitoring of seismicity can lead to improved understanding of the causes of induced seismic activity and ultimately, perhaps, to development of tools for predicting and preventing the occurrence of induced earthquakes.

Data Analysis Tools

Priorities for Developing Analytical Tools

- Develop techniques to optimize network design.
- Improve computer simulation and decision-support models.
- Identify indicator or "tracer" characteristics for tracking contaminants.

Monitoring consists of more than just collecting data. To be of use, the collected data must be analyzed, first in order to assure the quality of the data and subsequently to identify any underlying spatial or temporal trends in the data. Data analysis tools are integral components of successful monitoring networks. These tools usually consist of protocols and statistical and numerical computer programs. In addition to supporting quality assurance and interpretation of data, these tools can help optimize network performance in terms of identifying important locations for collecting data and types of data that are collected. The tools can also serve as important components of decision-support systems that are used to manage natural resources. For example, incorporation of ecosystems data into decision-support software can enable managers to evaluate the ecological tradeoffs of various energy-development alternatives (Haines and others, 2013).

Computer simulation models are valuable tools for data analysis; examples of simulation models include groundwater flow models, reservoir management models, and ecosystem models. Monitoring and simulation modeling are

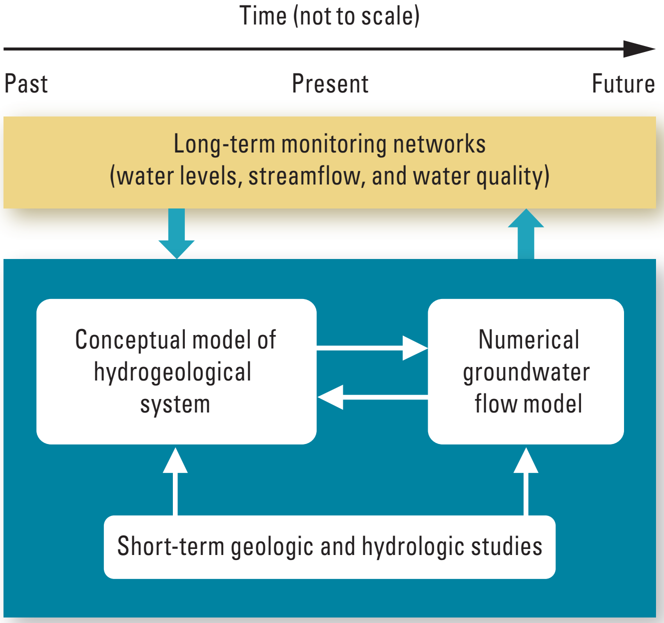


Figure 37. A framework for the integration of groundwater monitoring and groundwater flow modeling. The top row signifies a long-term network that is systematically monitored over time. The second row represents the development of models and their periodic updates in order to advance the understanding of how the aquifer system responds to human development, integrating new information, and addressing new questions as they arise. The vertical arrows represent a feedback loop in which long-term monitoring is used as input to modeling and modeling is used to evaluate long-term monitoring networks. (Modified from Alley, 2006)

complementary activities. Data are important for building conceptualizations of real systems and for calibrating computer simulation models, and simulation results provide feedback and insights into the adequacy of and gaps in monitoring data. An idealized framework for the integration of monitoring and modeling in the context of regional groundwater studies is illustrated in figure 37. Ideally, monitoring and modeling are part of a dynamic process in which the model and the monitoring networks are periodically updated based upon their synergistic output. Improved simulation models could provide more realistic representations of processes and could quantify uncertainties both in our knowledge of those processes and in simulation results. Results from these models can allow managers to predict where and when effects of energy operations might be realized and how those effects might be best mitigated.

Trends in environmental data can result from natural processes and from energy development or other human activities. Natural variations in shallow groundwater chemistry, for example, can complicate efforts to distinguish between natural, unaffected groundwater and groundwater that has been contaminated by energy-related activities. This problem can be alleviated if certain physical, chemical, or biological traits in data can be uniquely associated with specific energy-related activities and if those traits or "tracers" can be incorporated into network data-collection schemes. For example, most people can sense a leak in the natural gas line in their home by a familiar odor. Natural gas itself is odorless, so energy companies mix a chemical (methyl mercaptan) into the gas that they deliver to homes and businesses to produce an odor that makes leaks easy to detect. Environmental tracers are used in much the same way. Tracers can be specific compounds or

Naturally occurring methane is more prevalent in groundwater and surface water than previously assumed, so the presence of methane in a stream-water sample is not in and of itself evidence of human-induced contamination. Information on isotopic composition of carbon and hydrogen in methane could aid in identifying sources of methane in groundwater.

isotopic ratios of compounds that are in extracted fuels, native groundwater, injected wastewater, or geologic formations. Chemicals in fluids used in drilling, extraction, and hydraulic fracturing operations may also be useful as tracers. The identification of new tracers that can be used to study the effects of energy development on water and ecosystem resources and the incorporation of these tracers into the analytical schedules of water-quality monitoring programs would benefit a diverse group, including homeowners, ecosystem managers, water-resource managers, and energy-resource developers.

Research

Climate Change

Priorities for Studying Climate Change and Its Effects

- Reduce uncertainty in our understanding of past and future climates.
- Determine the effects of climate change on water resources (including the magnitude and frequency of floods and droughts) and ecosystems.
- Improve our understanding of the carbon cycle and its relation to climate.
- Evaluate the viability of geologic carbon sequestration.

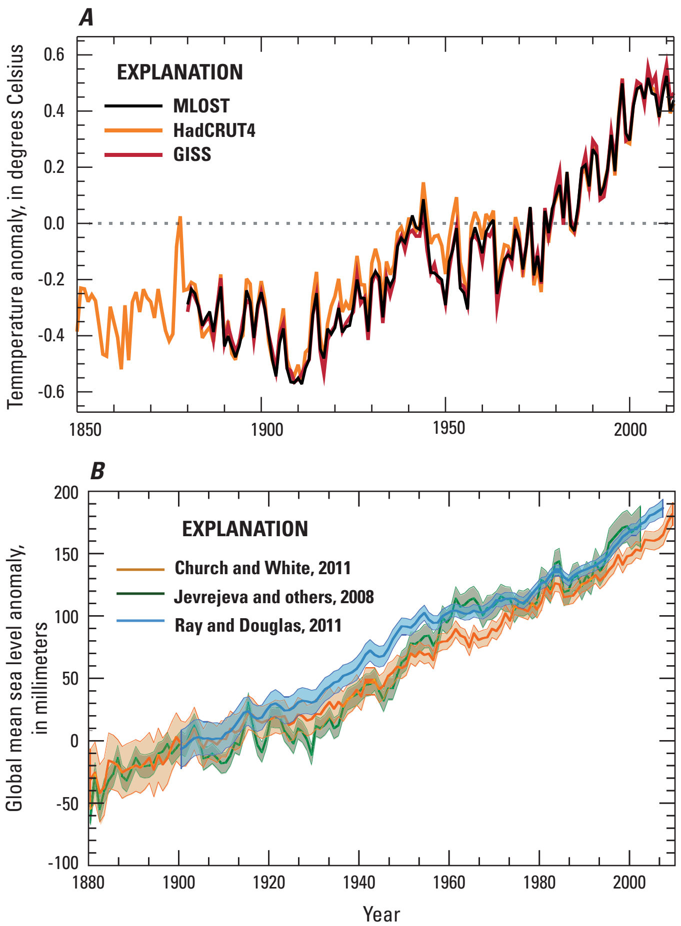


Figure 38. *A*, Annual global mean surface temperature anomalies from three data sets (HadCRUT4, GISS, and NCDC MLOST), and *B*, annual global mean sea level (GMSL) anomalies reconstructed from tide gages by three different approaches. All anomalies are relative to corresponding averages for the period 1961–1990. (Intergovernmental Panel on Climate Change, 2013)

Water and energy are intrinsically linked with climate through a variety of feedback mechanisms. Climate drives Earth's water cycle and, as such, is the single most important factor controlling long-term water availability. At the same time, water use and land use can influence climate. Energy production and use also affect climate. Over the course of the past 100 years, the Earth's average surface temperature has increased by about 1 °C, and global average sea level has risen steadily (in part due to melting snow and ice fields) (fig. 38). These trends result, at least partially, from energy production and use, primarily the combustion of fossil fuels and the subsequent emission of greenhouse gases, such as carbon dioxide and nitrous oxide, to the atmosphere (Intergovernmental Panel on Climate Change, 2013). Changes in climate and subsequent changes in water availability could place constraints on future options for energy production and use (U.S. Department of Energy, 2014).

Predictions of future climate trends generated with various global circulation models differ in the details, but consistent patterns appear for many regions. Of particular interest are the trends for the southwestern United States—temperature increases of 1 to 4 °C by the end of the 21st century (fig. 39) and slight decreases in precipitation (Intergovernmental Panel on Climate Change, 2013). The southwestern United States, with its semiarid to arid climate, already has limited water resources, but the population growth, commensurate increases in energy requirements, and increases in extraction of hydrocarbon fuels expected in the coming decades will stress those resources even further. The rising demand for water for energy production in this region must somehow be resolved with potentially reduced amounts of available water. The benefits of collaborative planning among energy and water providers and regulators are apparent (Hightower and Pierce, 2008; U.S. Department of Energy, 2014).

A recent study outlined how the hydrologic effects of climate change can affect energy production (U.S. Department of Energy, 2013b):

- The thermal efficiency of thermoelectric power plants and the transmission efficiency of electric grid networks would decline with increasing temperatures, resulting in more fuel consumption to produce a fixed amount of electricity.
- Decreased water availability could lead to reductions in electricity generating capacity.
- Hydroelectric power plants could see a reduction in electricity generation if droughts become more common.
- Increased temperatures would be accompanied by higher rates of potential evapotranspiration.
- Greater evaporation from reservoirs would mean increased water intensity for hydroelectricity.
- Increased storm intensities could lead to enhanced risk of damage to water and energy infrastructure.
- The vulnerability of coastal infrastructure to damage from rising sea levels might increase.
- Thawing permafrost in arctic regions would require modification of the methods used to extract hydrocarbon fuels in those regions.

Understanding the links among climate change, water, and energy requires some insight into past and future climate patterns, but this insight can be difficult to develop (Burkett and others, 2013). Hydrologic systems respond to short-term variability in weather patterns and long-term climate trends. Distinguishing between these two phenomena, although a difficult task, is key for developing a full understanding of climate change. Data-collection networks for the direct observation of climatic variables (such as precipitation, temperature, and stream and lake stage) have, in general, been in existence for fewer than 200 years. This information is vital for identifying current trends, but the period for which direct observations are available is quite short relative to the millions of years over which climate has been changing. Current understanding of past climates has been developed largely on the basis of indirect observations of fossils (Betancourt and others, 2000); geochemistry (Winograd and others, 1988); chemistry of ice cores, soils, and lake sediments (Petit and others, 1999); and tree rings (Gray and others, 2004). Predictions of future climate trends are generated by highly sophisticated global circulation models (Intergovernmental Panel on Climate Change, 2013). Different models generally predict similar trends, but there are important differences among predictions.

Reducing the uncertainty in our knowledge of past, current, and future climates is an important goal of earth science research. Improved techniques for reconstructing past climates, both in terms of means and variations of climatic variables, can reduce uncertainty and help guide adaptation and mitigation activities (Brekke and others, 2009). Continued monitoring will help to determine to what extent recent climatic patterns are a part of either long-term trends or short-term natural variability; this information can also provide some insight on the role of energy development in climate change. Improved methods for measuring and estimating precipitation, temperature, streamflow, and other variables may involve combining traditional approaches with data collected remotely from land-based and satellite-based systems. Enhanced data collection will also allow for better calibration of global circulation models, which could potentially lead to reductions in uncertainties in predictions of climate trends for coming decades and centuries.

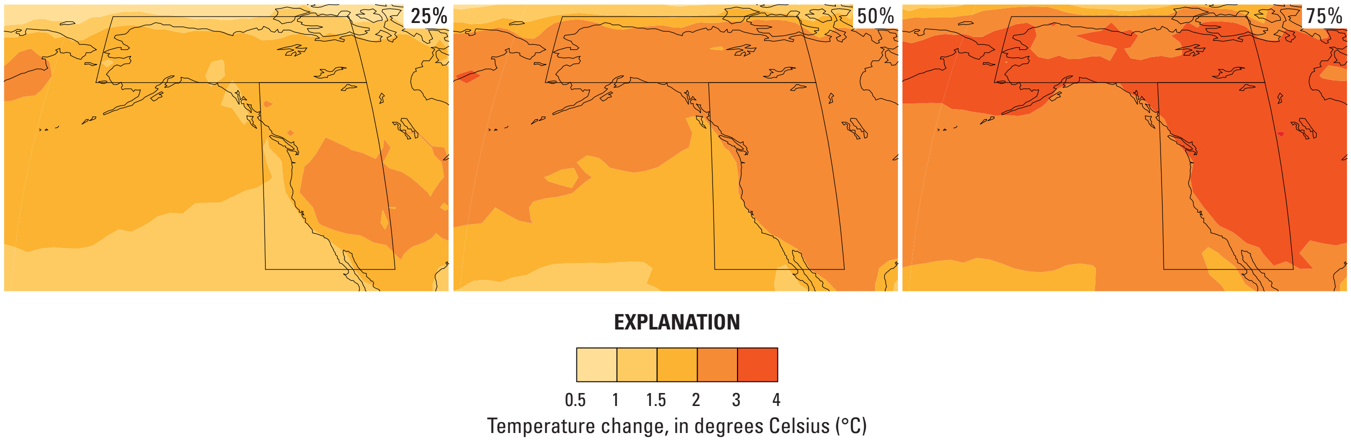


Figure 39. Predicted temperature change, in degrees Celsius, for western North America for June–August for the period 2081–2100 relative to average temperature for 1986–2005 (25th, 50th, and 75th percentile of distribution of CMIP5 ensemble model predictions for the RCP4.5 scenario). (Intergovernmental Panel on Climate Change, 2013)

Monitoring water and ecosystem resources over extended periods of time is crucial for identifying and understanding hydrologic and ecological trends and links to climatic trends (Brekke and others, 2009). The value of monitoring networks is addressed in an earlier section, but it is important to emphasize the role of resource monitoring in developing an understanding of climate change and its effects on natural and human-affected systems. Studies on how ecosystems adapted to changes in climate in the past can provide insight into how they may be affected in the future. In particular, ecosystems and species most vulnerable to the adverse effects of climate change can be identified, and studies can be conducted to determine how those vulnerabilities can be reduced.

The development of enhanced analytical techniques for characterizing floods, droughts, and other extreme hydrologic events can improve our understanding of the natural occurrence and variability of these events and support efforts to mitigate their effects. This work would involve studying the occurrence and severity of historical events and developing improved methods for analyzing the magnitude and frequency of past and recent floods, droughts, and rises in sea level. The adverse effects from high-intensity hydrologic events in the future can be reduced if maps of regions that will be vulnerable to these events can be produced. These maps would also benefit energy developers when planning future energy operations and infrastructure.

Carbon dioxide concentrations in the atmosphere are at their highest levels in at least the past 800,000 years (Luethi and others, 2008; Hönisch and others, 2009; Pagani and others, 2010). Developing a fundamental understanding of the role that carbon plays in climate change is an important research objective. Research focused on the interactions of natural carbon storage and exchange, climate, land use, and biogeochemical processes at all scales, from plot to global, is particularly useful. Also important are assessments of carbon storage in and exchange among ecosystems, geologic formations, water bodies, and the atmosphere. Earth science research relevant to geologic carbon sequestration (see Box K—Carbon Capture and Sequestration) includes assessing subsurface CO_2 storage capacities in geologic units; monitoring water levels, water quality, and seismic activity; and conducting intensive small-scale studies to gain a fuller understanding of the physical, geochemical, and biologic effects of the subsurface injection of CO_2. Monitoring freshwater aquifers is important to ensure the early detection of contaminants related to carbon sequestration. Tools for predicting where, when, and how injection operations induce earthquakes would benefit society greatly, as would innovations that could reduce the number and severity of these earthquakes.

Climate change has affected habitat for many wildlife species.

Byproducts and Waste Streams of Energy Development

Priorities for Studying Energy Byproducts and Waste

- Quantify and characterize waste streams.
- Determine the fate of waste streams and their effects on water and ecosystem resources.
- Identify alternative uses or means of disposition for wastes.

The Earth sciences provide a foundation for addressing issues associated with the broad spectrum of byproducts and waste streams related to energy production and use. An assessment of the quantities and physical, chemical, and biological characteristics of waste material is a requisite first step in evaluating alternative options for disposition of the material, options that include treatment, surface discharge, subsurface discharge, and beneficial use or reuse. Equally important is research on the direct and indirect effects of energy waste streams on water and ecosystem resources at local, regional, and national scales. Detailed chemical and isotopic characterization can help to identify sources of contaminants in freshwater systems and can provide insight into the processes that control contaminant movement. The identification of environmentally sound reuses or alternative means for disposition of byproducts such as produced water and carbon combustion residues has tangible benefits—it would reduce the requirements for freshwater and the need for waste disposal.

Atmospheric emissions of greenhouse gases, other gases, and particulates raise concerns regarding climate change and the impairment of water quality by acid deposition, mercury, and other contaminants (see Box J—Energy, Atmospheric

Emissions, and Water Quality). Carbon dioxide is an important atmospheric greenhouse gas; coal-fired power plants and motor vehicles are the two largest sources of carbon dioxide emissions, respectively. Substantial amounts of methane, another potent greenhouse gas, can also be emitted by oil and natural gas wells and distribution systems. Sulfur dioxide, nitrogen, and mercury emissions from coal-fired plants and other sources can affect water quality. The U.S. Environmental Protection Agency, responsible for regulating and monitoring atmospheric emissions in the United States, publishes annual estimates of emissions for the major greenhouse gases (U.S. Environmental Protection Agency, 2013b).

The acidity of precipitation (and dry deposition) and the geographic distribution of it across the United States can only be determined with a dispersed network of collection sites. The National Atmospheric Deposition Program maintains the largest such network in the United States. Initiated in 1977, the program supports a network of sites where precipitation is collected weekly; data on acidity and other constituents are available for no cost (*http://nadp.sws.uiuc.edu/NADP/*). Data from networks such as this were instrumental in documenting the extent and severity of acid rain in the 1970s and 1980s; they remain important in tracking trends over time. Results of extensive research programs identified the deleterious effects of acid rain and associated contaminants on ecosystems, soils, water, and vegetation (Likens, 2011). From the 1980s to the present, data collection and research have provided a basis for revised regulations and policy; these revisions have resulted in substantial reductions in annual atmospheric deposition rates of sulfate (*http://nadp.sws.uiuc.edu/maplib/ani/so4_dep_ani.pdf*) and nitrate (*http://nadp.sws.uiuc.edu/maplib/ani/no3_dep_ani.pdf*) in the United States. Continued resource monitoring and research can enhance our understanding of the effects of atmospheric deposition of contaminants in a number of ways, for example, by identifying factors that promote or retard the transport of pollutants such as mercury within hydrologic and biologic systems.

In addition to atmospheric emissions, thermoelectric power plants could have additional byproducts of concern, depending on cooling system design and fuel type. Once-through cooling systems can result in high heat loads to the streams or lakes that provide the cooling water. The resulting increased temperature in the water body can have adverse effects on aquatic ecosystems; these effects are compounded during times of drought when the ecosystems are already under stress (Electric Power Research Institute, 2012). Coal combustion products (coal ash) can be used in a number of beneficial ways, but recent research has raised concerns on the environmental impacts of its reuse and disposal (Pandey and Singh, 2010; Ruhl and others, 2012). Annual production amounts of coal ash are published by the American Coal Ash Association (American Coal Ash Association, 2014), but there is no available data base on the chemistry of coal ashes. The U.S. Environmental Protection Agency has recently issued new regulations for the disposition of coal ash (U.S. Environmental Protection Agency, 2014a).

Produced water is the largest byproduct (by volume) of oil and natural gas production. Rates of extraction and chemical characteristics of produced waters vary with location, and these variations have important implications on management, use, and potential environmental impacts of the water. Information on volumes and quality of produced waters is important for identifying potential beneficial uses. The information also can be used to assess saline resources, identify sources of saline water suitable for operations such as hydraulic fracturing, determine the feasibility of wastewater injection operations, and further research on geologic carbon sequestration. Unfortunately, there is no system in place for tracking rates of produced-water extraction at the national level. A database on water-quality characteristics of produced waters from most basins in the United States is maintained by the U.S. Geological Survey (*http://energy.cr.usgs.gov/prov/prodwat/data.htm*). Information contained in that database includes well location and depth, geologic formation, and concentrations of major and minor ions, organic compounds, radionuclides, and chemical isotopes. Along with other uses, this water-quality information potentially could be used to determine the age and origin of water in saline aquifers, which in turn could provide insight on hydraulic connections to freshwater reservoirs.

Abandoned coal and uranium mine lands are the main source of acid mine drainage. Under the leadership of the Bureau of Land Management, a number of Federal agencies have collaborated to create the Abandoned Mine Lands Portal (*http://www.abandonedmines.gov/index.html*), which provides information on types and locations of abandoned sites and the environmental, health, and safety concerns associated with each site. Most abandoned coal mines are in the eastern United States (primarily West Virginia, Pennsylvania, and Kentucky), whereas most abandoned uranium mine lands are

Oilfield waste arrives by tanker truck at a wastewater disposal facility near Platteville, Colorado. After removal of solids and oil, the wastewater is injected into a deep well for permanent storage underground.

located in 14 western states. Acid mine drainage can occur for more than 100 years after a site has been abandoned. Research has already shown how acidic waters are created from mine-waste piles and how acidification of groundwater and streams can impair ecosystems (for example, Nordstrom and Alpers, 1999). Remediation of abandoned sites is expensive, and progress on remediation is hindered by limited funding. Research can provide a better understanding of the physical, geochemical, and biological processes that contribute to the natural attenuation of contaminants from acid mine drainage. Also important is the development of tools for evaluating alternative approaches for reducing the adverse effects of acid mine drainage on streams (Walton-Day and others, 2012; Runkel and others, 2012). Advances in research could lead to more cost-effective methods for site remediation.

The many thousands of abandoned, unsealed wells that are present in mature oil and gas fields across the United States present an important legacy issue to consider. Most States have records showing locations for wells that were abandoned in the most recent decades, but available funding for sealing these wells is not always sufficient to cover the task. More problematic are wells that were abandoned in the late 1800s and early and middle decades of the 1900s; records of these wells are largely nonexistent, and locating these wells can be extremely difficult. Aerial geophysics is one area of research that has proved to be useful in locating abandoned wells (fig. 40).

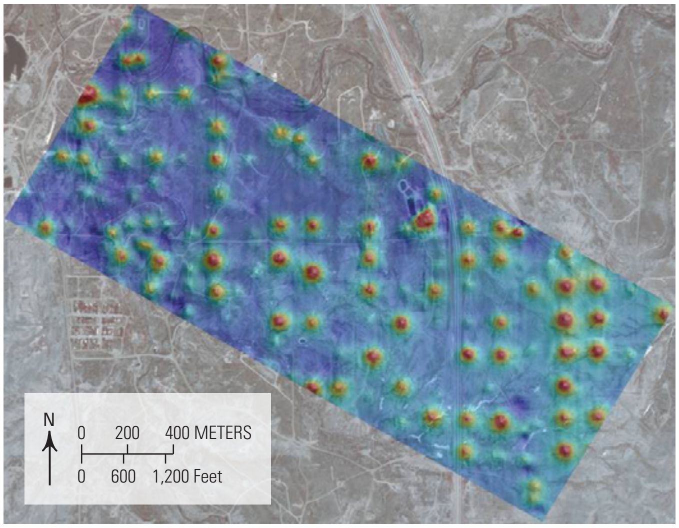


Figure 40. False color map showing the response from helicopter electromagnetic surveys for a portion of the Salt Creek oilfield near Casper, Wyoming. Warmer colors indicate the presence of highly conductive materials, in this case steel casings from abandoned oil wells. This image is a reminder of the remnants of legacy oil and gas operations in many portions of the United States. (Image courtesy of Richard Hammack, National Energy Technology Laboratory, Pittsburgh, Pennsylvania)

Contamination of groundwater and surface water by nutrients contained in fertilizers has long been a concern in the midwestern United States (Gilliom and others, 2006). Because much of the corn and soybeans grown in the United States is used as biofuel feedstocks, some of the contamination can be attributed to energy production. Our knowledge of the extent of nutrient contamination, the mechanisms by which nutrients and other agricultural chemicals are transported, and the effects of the contamination on ecosystems has been obtained through programs for monitoring water quality and ecosystem health and by large-scale research efforts. As an example, recent research has shown that between 2006 and 2011, approximately 530,000 hectares of native grass lands in the western corn belt of the United States were converted to row crops, primarily corn and soybeans (Wright and Wimberly, 2013). The primary driving force for this large-scale conversion is the historically high grain prices, which have been created in large part by the demand for biofuel feedstocks. Continued monitoring and additional research can help in developing a clear understanding of the effects that land conversion and other agricultural operations have on water quality and ecosystems and in identifying potential improvements in farming practices.

Emerging Energy Development Technologies

Priorities for Studying the Effects of New Technologies

- Improve our understanding of hydraulic fracturing.
- Assess hydrologic and environmental impacts of emerging technologies.

Technology is continually evolving. Evaluating the viability and hydrological and environmental impacts of new energy development technologies is an important but challenging task for the earth sciences. Once an energy-development technique is found to be effective and economical, it might be implemented on a widespread basis before researchers and regulators can identify and analyze all the associated effects. Carefully designed data-collection networks and directed research can improve our understanding of these technologies and provide useful information to resource managers, energy developers, and the general public.

Recent advancements in technology for extracting hydrocarbon fuels have left large gaps in our understanding of effects associated with the application of these technologies. The rapid expansion in use of hydraulic fracturing (see Box E—Hydraulic Fracturing) combined with directional drilling has raised concerns in regard to water quality—specifically, the possible subsurface migration of methane and saline fluids to freshwater supplies and the disposition of produced waters. Groundwater-quality monitoring is useful for detecting subsurface migration of saline fluids. Data obtained from laboratory experiments and intensive, site-specific field monitoring can improve our understanding of the nature of the fractures created by hydraulic fracturing, in terms of density, aperture, connectivity, and vertical and horizontal extent. These data can also provide insight on fluid movement, chemical reactions, and seismic activity that could occur as a result of hydraulic fracturing and other operations. For example, fluids produced from some Marcellus Shale gas wells have very high salinities. Identifying the source of that salinity (naturally occurring brines or dissolution of reservoir minerals) can shed light on how hydraulic fracturing affects a reservoir. An approach looking at the relationships between the sodium, chloride, and bromide concentrations in produced water has been developed for differentiating between these sources (Engle and Rowan, 2013).

New technologies hold great promise for solving important energy and water problems (U.S. Department of Energy, 2014), but the water quantity and quality issues associated with these technologies are not always apparent. These technologies include, for example, geologic sequestration of carbon dioxide, enhanced geothermal systems, cellulosic bioethanol, and algal biodiesel. Research into the water-related needs and issues of new technologies can help to determine their viability in different regions. Each proposed technology has specific issues, but the core issues of freshwater availability, protection of water quality, and the availability and use of saline or wastewater form a common thread among all energy development technologies. Resource assessment and monitoring networks can provide information for evaluating the hydrological and environmental effects of new technologies on a broad scale, but more detailed data collection on a site-specific scale might be required. In addition, in-depth hydrogeological and geochemical characterizations on both regional and local scales will be necessary for operations such as geologic carbon sequestration and enhanced geothermal systems. As the use of new technologies ramps up, additional important research issues may unfold.

Energy Use for Water

Priorities

- Improve our understanding of managed aquifer recharge in different settings.
- Protect water quality and evaluate natural processes for remediating contaminated water.

Research plays an important role in efforts to minimize the energy intensity of the water-use cycle. Research in engineering fields provide perhaps the most obvious examples—research on more energy-efficient hot-water heaters and pumps or research on extracting energy from wastewater—but earth science research also has an important role to play. Earth science research can identify new water supplies, better characterize the quantity and quality of existing water supplies, suggest ways to avoid contamination of water supplies, and evaluate alternative approaches for remediating contaminated water.

In situations where local freshwater supplies are being depleted, local saline groundwater could be an attractive supplemental water source compared to more distant freshwater sources that might have a high energy cost associated with conveyance. Earth science research can answer questions about the quantity and quality of the saline groundwater resource, as well as how much water a saline aquifer can yield to wells. Such information is crucial to the planning process of water managers and engineers. Before construction began on El Paso's desalination plant, hydrogeologic monitoring data and results from a groundwater-flow model were used to determine optimum locations for the plant and the pumping wells that feed it (Heywood and Yager, 2003; El Paso Water Utilities, 2007).

Managed aquifer recharge (MAR) is used to supplement groundwater supplies and has the potential to reduce overall energy use for delivering water to residential, agricultural, and industrial interests. The viability of MAR systems depends, among other factors, on the hydraulic and geochemical characteristics of the receiving aquifers. Research to better understand how exactly these characteristics influence the storage and recovery processes can lead to more efficient system operations. Developing methods to estimate these characteristics for different areas on the basis of existing information would facilitate the selection of appropriate areas for managed aquifer recharge.

Continued on page 90

Saving Energy and Saving Water

Energy consumed for water represents an important part of the Nation's energy demand, and that consumption is likely to increase in the future as population increases. Fortunately, current and future energy requirements could be reduced by saving water. Opportunities to save water exist at each stage of the water-use cycle. Reducing the leakage of water from conveyance structures, pumps in water and wastewater treatment plants, distribution pipelines, residential plumbing, and other components of the cycle represents one such opportunity. Water heating consumes more energy than any other part of the water-use cycle, so saving water at that stage could result in substantial energy savings. Using less cold water in indoor residential, commercial, and industrial applications, such as by installing low-flow toilets, would save the energy embedded at the early stages (water conveyance, treatment, and distribution) and at later stages (wastewater collection and treatment) of the water-use cycle. Using less water in outdoor residential, commercial, and industrial applications would also save the energy embedded at the early stages of the water-use cycle. And as has been stated several times, protecting the quality of water could save energy associated with some types of advanced water treatment that might be needed to remove contaminants from water. Finally, saving water has the added benefits of reducing the carbon footprint of the water-use cycle and allowing more water to remain in aquifers, streams, lakes, and other water bodies for environmental uses.

Although estimates of the actual amounts of water withdrawn and consumed in the United States for the development and use of energy are clouded with uncertainty, it is clear that energy-related water withdrawal and consumption can be reduced in several ways. Individuals, businesses, and government agencies can simply alter their use of the operations that consume energy, for example, turning off unused lights or lowering the setting on the home thermostat in winter. In addition, methods for developing energy that are less water intensive can be improved and expanded—generation of electricity by passive solar and wind methods consume negligible amounts of water. Development of more energy-efficient processes will also lead to a reduction of water withdrawal and consumption. For example, the U.S. Environmental Protection Agency finalized new fuel-economy standards for cars and light trucks in 2012 that call for an average fuel-economy of 23 km/L (54.5 miles per gallon) by the year 2025 (U.S. Environmental Protection Agency, 2012a). It is estimated that the standards will reduce daily consumption of hydrocarbon fuels in the United States by about 350 million L/d. The reduced consumption of transportation fuels translates to a reduced amount of water needed to extract and process those fuels.

Protecting water quality saves energy—clean water requires less treatment than contaminated water. Important water-quality issues that are being addressed through earth science research include the identification of sources of contaminants in water supplies, the explanation of temporal variability in contaminant concentrations, and the development of an understanding of why and where natural attenuation processes can remove contaminants from water supplies. For example, research done in the vicinity of a public-supply well owned by the City of Modesto, California, was instrumental in determining the source of nitrate and uranium in the well water and identifying well-operation practices that could minimize the contamination (Jurgens and others, 2008). In Lincoln, Nebraska, research explained why and when concentrations of the pesticide atrazine were changing over time in water from the city's municipal wells (Carr, 1993; Verstraeten and others, 1999). Such information could be used by water utilities to better manage their treatment process during periods of high contaminant levels either by reducing the intake of water or by blending it with cleaner water. Other studies have explained why natural attenuation processes are effective in protecting water supplies in some locations but not in others (for example, McMahon and others, 2008; Bradley and Chapelle, 2010). Information like this could be used to select new locations for water wells or water intakes to take advantage of natural attenuation processes. Earth science research can also assist in evaluating various alternatives for the disposition of byproducts of wastewater treatment processes. Operations such as the land application of biosolids and the use of treated wastewater for managed aquifer recharge projects may be energy and water efficient, but only if the quality of existing water supplies are not degraded.

Conclusions

Two important challenges facing the United States are preserving sustainable supplies of freshwater for humans and ecosystems and ensuring adequate sources of energy for future generations. These challenges need not be viewed as mutually exclusive options, even though competition for limited water and energy resources already is occurring in some parts of the country. Conflicts can be avoided and water and energy resources can be protected with prudent management strategies. The material presented in this report is intended to provide resource managers and the general public with an enhanced appreciation of the complex ways in which water and energy are interconnected.

Future development of water and energy resources within the United States will be guided by policy decisions at local, State, and national levels. Considerations such as population trends, public opinion, the economy, and technology factor into water and energy policies; however, the foundation needed for informed policy decisions is provided by earth science data collection and research. The role of science is to identify and analyze important technical issues, to describe potential solutions to relevant problems, and to support informed decision making by communicating findings to resource managers, energy producers, and the public. Science improves our understanding of key processes, such as the chemical, physical, and biological reactions occurring in a reservoir during hydraulic fracturing. Science also provides a platform for identifying potential environmental or human health ramifications of energy development. To remain relevant, earth science data-collection and research efforts must continue to evolve as new development technologies emerge.

Current understanding of the water-energy nexus is limited by uncertainty in our knowledge of important issues, such as the amount of freshwater that is available and the amount of water that is used in energy development. Predictions of future water and energy needs and availability can be improved if this uncertainty can be reduced. Water and energy resource management efforts are also complicated by the fact that policy makers, resource managers, and water and energy developers are often faced with a series of tradeoffs in their decisions. One example is balancing the cost of added water requirements and potential water-quality issues against the benefit of reduced atmospheric emissions of greenhouse gases at coal-fired power plants by adopting carbon capture and geologic sequestration strategies. Earth science data collection and research can help to elucidate the benefits and pitfalls of tradeoff options.

Advances in technology might eventually alleviate some of the competition associated with water and energy development. Adoption of new technologies can result in considerable deviations between actual and predicted trends. Consider, for example, the effects of recent developments in directional drilling and hydraulic fracturing on estimates of natural gas reserves in the United States. In 1993, the Energy Information Administration estimated natural gas reserves in the United States at about 5 trillion m^3. Seventeen years later (2010), those estimates had increased to 9 trillion m^3, largely because these new technologies allow recovery of gas that was previously believed to be inaccessible. Technologies such as algal biodiesel, bioethanol from second-generation feedstocks, and enhanced geothermal systems hold great promise, but the economic viability of these technologies has yet to be demonstrated at commercial scales, and their water requirements are largely unknown. In planning for future water and energy needs, policy makers may be drawn by the allure of promising, but not fully developed, technologies to address pressing water and energy concerns. A more pragmatic approach for water and energy policy planners is to seek solutions to our problems solely on the basis of existing technology. Technology will continue to evolve in the future, and new advances will no doubt contribute to our understanding of and our ability to address the important water-energy issues that we face as a Nation. Prudent resource-management strategies will be able to incorporate new advances as they become available.

References Cited

Adee, Sally, and Moore, S.K., 2010, In the American Southwest, the energy problem is water: IEEE Spectrum, May 28, 2010, accessed July 16, 2013, at *http://spectrum.ieee.org/energy/environment/in-the-american-southwest-the-energy-problem-is-water*.

Alberta Government, 2013, Alberta oil sands industry—Quarterly update, summer 2013: Alberta Government, 16 p., accessed November 5, 2013 at *http://www.albertacanada.com/files/albertacanada/AOSID_Quarterly_Update_Summer2013.pdf*.

Alley, W.M., 2006, Tracking U.S. groundwater—Reserves for the future?: Environment, v. 48, no. 3, p. 10–25.

Alley, W.M., and Alley, Rosemarie, 2013, Too hot to touch—The problem of high-level nuclear waste: Cambridge, U.K., Cambridge University Press, 383 p.

Alley, W.M., Evenson, E.J., Barber, N.L., Bruce, B.W., Dennehy, K.F., Freeman, M.C., Freeman, W.O., Fischer, J.M., Hughes, W.B., Kennen, J.G., Kiang, J.E., Maloney, K.O., Musgrove, MaryLynn, Ralston, Barbara, Tessler, Steven, and Verdin, J.P., 2013, Progress toward establishing a national assessment of water availability and use: U.S. Geological Survey Circular 1384, 36 p. (Also available at *http://pubs.usgs.gov/circ/1384/*.)

American Coal Ash Association, 2014, 2012 Coal combustion product (CCP) production and use survey report: American Coal Ash Association, accessed on August 9, 2014, at *http://www.acaa-usa.org/Portals/9/Files/PDFs/revisedFINAL2012CCPSurveyReport.pdf*.

Averyt, Kristen; Fisher, Jeremy; Huber-Lee, Annette; Lewis, Aurana; Macknick, Jordan; Madden, Nadia; Rogers, John; and Tellinghuisen, Stacy, 2011, Freshwater use by U.S. power plants—Eectricity's thirst for a precious resource: Cambridge, Mass., Union of Concerned Scientists, Energy and Water in a Warming World Initiative, 53 p.

Bakken, T.H., Killingtveit, A., Engeland, K., Alfredsen, K., and Harby, A., 2013, Water consumption from hydropower plants—Review of published estimates and assessment of the concept: Hydrologic and Earth Systems Science, v. 17, p. 3983–4000.

Bern, C.R., Breit, G.N., Healy, R.W., Zupancic, J.W., and Hammack, Richard, 2013a, Deep subsurface drip irrigation using coal-bed sodic water—Part I. Water and solute movement: Agricultural Water Management, v. 118, p. 122–134.

Bern, C.R., Breit, G.N., Healy, R.W., and Zupancic, J.W., 2013b, Deep subsurface drip irrigation using coal-bed sodic water—Part II. Geochemistry: Agricultural Water Management, v. 118, p. 135–149.

Betancourt, J.L., Latorre, C., Rech, J.A., Quade, J., and Rylander, K.A., 2000, A 22,000-year record of monsoonal precipitation from northern Chile's Atama Desert: Science, v. 289, p. 1542–1546.

Bexte, D.C., Willis, M., De Bruijn, G.G., Eitzen, B., and Fouillard, E., 2008, Improved cementing practice prevents gas migration: World Oil Online, v. 229, no. 6, accessed September 11, 2013, at *http://www.worldoil.com/June-2008-Improved-cementing-practice-prevents-gas-migration.html*.

Bowen, Z.H., Aldridge, C.L., Anderson, P.J., Chong, G.W., Drummond, M.A., Homer, Colin, Johnson, R.C., Kauffman, M.J., Knick, S.T., Kosovich, J.J., Miller, K.A., Owens, Tom, Shafer, Sarah, and Sweat, M.J., 2009, U.S. Geological Survey science strategy for the Wyoming Landscape Conservation Initiative: U.S. Geological Survey Scientific Investigations Report 2008–5195, 26 p.

Boyd, James, and Banzhaf, Spencer, 2006, Water are ecosystem services?—The need for standardized environmental accounting units: Washington, D.C., Resources for the Future, 29 p.

Bradley, P.M., and Chapelle, F.H., 2010, Biodegradation of chlorinated ethenes, chap. 3 *of* Stroo, H.F., and Ward, C.H., eds., In situ remediation of chlorinated solvent plumes: New York, Springer, p. 39–67.

Brekke, L.K., Kiang, J.E., Olsen, J.R., Pulwarty, R.S., Raff, D.A., Turnipseed, D.P., Webb, R.S., and White, K.D., 2009, Climate change and water resources management—A federal perspective: U.S. Geological Survey Circular 1331, 65 p. (Also available at *http://pubs.usgs.gov/circ/1331/*.)

Burkett, V.R., Kirtland, D.A., Taylor, I.L., Belnap, Jayne, Cronin, T.M., Dettinger, M.D., Frazier, E.L., Haines, J.W., Loveland, R.R., Milly, P.C.D., O'Malley, Robin, Thompson, R.S., Maule, A.G., McMahon, Gerard, and Streigl, R.G., 2013, U.S. Geological Survey climate and land use change science strategy—A framework for understanding and responding to global change: U.S. Geological Survey Circular 1383–A, 43 p. (Also available at *http://pubs.usgs.gov/circ/1383a/*.)

Byrnes, A.P., 2011, Role of induced and natural imbibition in frac fluid transport and fate in gas shales [slide presentation], *in* Proceedings of the technical workshops for hydraulic fracturing study—Fate and transport, Arlington, Va., March 28–29, 2011: U.S. Environmental Protection Agency, 28 slides, accessed May 15, 2013, at *http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/upload/roleofinducedandnaturalimbibitioninfracfluid.pdf*.

California Department of Water Resources, 2002, Management of the California State Water Project—Covers activities during calendar year 2000: Department of Water Resources Bulletin 132–01, 393 p., accessed July 8, 2014, at *http://www.water.ca.gov/swpao/docs/bulletins/bulletin132/Bulletin132-01.pdf*.

California Department of Water Resources, 2009, California water plan update 2009—Integrated water management, v. 2—Resource management strategies: Department of Water Resources Bulletin 160–09, 662 p., accessed June 20, 2013, at *http://www.waterplan.water.ca.gov/cwpu2009/index.cfm#volume2*.

California Energy Commission, 2005, California's water-energy relationship—Final staff report: California Energy Commission, CEC–700–2005–011–SF, 180 p., accessed July 5, 2012, at *http://www.energy.ca.gov/2005publications/CEC-700-2005-011/CEC-700-2005-011-SF.PDF*.

California Sustainability Alliance, 2008, The role of recycled water in energy efficiency and greenhouse gas reduction: California Sustainability Alliance, 89 p., accessed March 12, 2013, at *http://sustainca.org/library/publications?page=1*.

Carr, J.D., 1993, Atrazine in the Platte River and Lincoln municipal water: Great Plains Research, v. 5, no. 2, p. 167–188.

Carter, K.M., Harper, J.A., Schmid, K.W., and Kostelnik, Jaime, 2011, Unconventional natural gas resources in Pennsylvania—The backstory of the modern Marcellus Shale play: Environmental Geosciences, v. 18, no. 4, p. 217–257, doi:*10.1306/eg*.09281111008.

Cederstrand, J.R., and Becker, M.F., 1999a, Digital map of geologic faults for the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Open-File Report 99–261, accessed September 29, 2014, at *http://water.usgs.gov/GIS/metadata/usgswrd/XML/ofr99-261.xml*.

Cederstrand, J.R., and Becker, M.F., 1999b, Digital map of areas of little or no saturated thickness for the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Open-File Report 99–266, accessed September 29, 2014, at *http://water.usgs.gov/GIS/metadata/usgswrd/XML/ofr99-266.xml*.

Center for Sustainable Systems, 2013, U.S. wastewater treatment factsheet: Ann Arbor, University of Michigan, Center for Sustainable Systems publication no. CSS04-14, 2 p., accessed March 20, 2014, at *http://css.snre.umich.edu/css_doc/CSS04-14.pdf*.

Charpentier, R.R., and Cook, T.A., 2010, Improved USGS methodology for assessing continuous petroleum resources: U.S. Geological Survey Data Series 547, 30 p. (Also available at *http://pubs.usgs.gov/ds/547*.)

Chisti, Yusuf, 2008, Biodiesel from microalgae beats bioethanol: Trends in Biotechnology, v. 26, no. 3, p. 126–131, *http://dx.doi.org/10.1016/j.tibtech.2007.12.002*.

Church, J.A., and White, N.J., 2011, Sea-level rise from the late 19th to the early 21st century: Surveys in Geophysics, v. 32, p. 585–602.

City of Houston, 2013, Wastewater facilities and maintenance section: City of Houston, Public Utilities Division, accessed May 13, 2013, at *http://www.publicworks.houstontx.gov/utilities/wwtms.html*.

City of Tigard, 2014, Aquifer storage and recovery (ASR): City of Tigard, accessed September 25, 2014, at *http://www.tigard-or.gov/city_hall/departments/public_works/asr.asp*.

Clark, C.E., and Veil, J.A., 2009, Produced water volumes and management practices in the United States: Argonne National Laboratory, 60 p.

Cocca, Paul, 2001, Mercury maps—A quantitative spatial link between air deposition and fish tissue: U.S. Environmental Protection Agency Report EPA-823-R-01-009, 25 p., accessed March 20, 2014, at *http://water.epa.gov/scitech/datait/models/maps/upload/2006_12_27_models_maps_report.pdf*.

Cohen, Ronnie; Nelson, Barry; and Wolff, Gary, 2004, Energy down the drain—The hidden costs of California's water supply: Oakland, Calif., Pacific Institute, and Natural Resources Defense Council, 85 p., accessed July 5, 2012, at *http://pacinst.org/wp-content/uploads/sites/21/2013/02/energy_down_the_drain3.pdf*.

Coleman, J.L., Milici, R.C., Cook, T.A., Charpentier, R.R., Kirshbaum, Mark, Klett, T.R., and Pollastro, R.M., 2011, Assessment of undiscovered oil and gas resources of the Devonian Marcellus Shale of the Appalachian Basin Province, 2011: U. S. Geological Survey Fact Sheet 2011–3092, 2 p. (Also available at *http://pubs.usgs.gov/fs/2011/3092*.)

Collier, Michael, Webb, R.H., and Schmidt, J.C., 1996, Dams and rivers—A primer on the downstream effects of dams: U.S. Geological Survey Circular 1126, 94 p. (Also available at *http://pubs.er.usgs.gov/publication/cir1126*.)

Corio, Emily, 2008, DEP prioritizes acid mine drainage stream cleanup: West Virginia Public Broadcasting, accessed July 16, 2013, at *http://www.wvpubcast.org/newsarticle.aspx?id=6212*.

Curtright, A.E., and Giglio, K., 2012, Coal mine drainage for Marcellus Shale natural gas extraction—Proceedings and recommendations from a roundtable on feasibility and challenges: Rand Corporation, 67 p., accessed March 20, 2014, at *http://www.rand.org/pubs/conf_proceedings/CF300.html*.

Daily, Gretchen, ed., 1997, Nature's services—Societal dependence on natural ecosystems: Washington, D.C., Island Press, 392 p.

Dakota Gasification Company, 2012, Gasification: Dakota Gasification Company, accessed November 24, 2014, at *http://www.dakotagas.com/Gasification/index.html*.

Davies, R.J.; Mathias, S.A.; Moss, Jennifer; Hustoft, Steinar; and Newport, Leo, 2012, Hydraulic fractures—How far can they go?: Marine and Petroleum Geology, v. 37, no. 1, p. 1–6.

Davies, W.E., Bailey, J.F., and Kelly, D.B., 1972, West Virginia's Buffalo Creek Flood—A study of the hydrology and engineering geology: U.S. Geological Survey Circular 667, 32 p. (Also available at *http://pubs.er.usgs.gov/publication/cir667*.)

Denver Water, 2014, The treatment process: Denver Water, accessed August 21, 2014, at *http://www.denverwater.org/WaterQuality/TreatmentProcess/*.

DeOreo, W.B., and Mayer, P.W., 2001, The end uses of hot water in single family homes from flow trace analysis: Boulder, Colo., Aquacraft Water Engineering & Management, 11 p., accessed July 20, 2012, at *http://www.aquacraft.com/node/35*.

Diehl, T.H., 2012, Estimating forced evaporation from surface water, *in* Third Thermal Ecology and Regulation Workshop, Maple Grove, Minn., October 11–12, 2011, Proceedings: Palo Alto, Calif., Electric Power Research Institute, 8 p.

Diehl, T.H., and Harris, M.A., 2014, Withdrawal and consumption of water by thermoelectric power plants in the Unites States, 2010: U.S. Geological Survey Scientific Investigations Report 2014–5184, 28 p.

Diehl, T.H., Harris, M.A., Murphy, J.C., Hutson, S.S., and Ladd, D.E., 2013, Methods for estimating water consumption for thermoelectric power plants in the United States: U.S. Geological Survey Scientific Investigations Report 2013–5188. (Also available at *http://pubs.usgs.gov/sir/2013/5188*.)

DiPippo, Ronald, 2007, Ideal thermal efficiency for geothermal binary plants: Geothermics, v. 36, p. 276–285.

Drost, B.W., and Lombard, R.E., 1978, Water in the Skagit River basin, Washington: Washington Department of Ecology Water-Supply Bulletin 47, 247 p.

Dubrovsky, N.M.; Burow, K.R.; Clark, G.M.; Gronberg, J.M.; Hamilton P.A.; Hitt, K.J.; Mueller, D.K.; Munn, M.D.; Nolan, B.T.; Puckett, L.J.; Rupert, M.G.; Short, T.M.; Spahr, N.E.; Sprague, L.A., and Wilber, W.G., 2010, The quality of our Nation's water—Nutrients in the Nation's streams and groundwater, 1992–2004: U.S. Geological Survey Circular 1350, 174 p. (Also available at *http://pubs.usgs.gov/circ/1350*.)

Duffield, W.A., and Sass, J.H., 2003, Geothermal energy—Clean power from the Earth's heat: U.S. Geological Survey Circular 1249, 36 p. (Also available at *http://pubs.usgs.gov/cir/1249*.)

Duncan, D.W., and Morrissey, E.A., 2011, The concept of geologic carbon sequestration: U.S. Geological Survey Fact Sheet 2010–3122, 2 p. (Also available at *http://pubs.usgs.gov/fs/2010/3122*.)

Eaton, Joe, 2012, Record heat, drought pose problems for U.S. electric power: National Geographic News, August 17, 2012, accessed July 23, 2013, at *http://news.nationalgeographic.com/news/energy/2012/08/120817-record-heat-drought-pose-problems-for-electric-power-grid/*.

El Paso Water Utilities, 2007, Desalination plant: El Paso Water Utilities, Public Service Board, accessed September 3, 2014, at *http://www.epwu.org/water/desal_info.html*.

Electric Power Research Institute, 2002, Water and sustainability, v. 4. U.S. electricity consumption for water supply and treatment—The next half century: Palo Alto, Calif., Electric Power Research Institute Topical Report 1006787, 93 p., accessed July 5, 2012, at *http://www.circleofblue.org/waternews/wp-content/uploads/2010/08/EPRI-Volume-4.pdf*.

Electric Power Research Institute, 2009, Program on technology innovation—Electrical efficiency through water supply technologies—A road map: Electric Power Research Institute Technical Report 1019360, 104 p., accessed July 11, 2013, at *http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001019360*.

Electric Power Research Institute, 2012, Third Thermal Ecology and Regulation Workshop, Maple Grove, Minn., October 11–12, 2011, Proceedings: Electric Power Research Institute, 450 p., accessed April 29, 2013, at *http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001025382*.

Ellsworth, W.L., 2013, Injection-induced earthquakes: Science, v. 341, no. 6142, *http://dx.doi.org/10.1126/science.1225942*.

Engle, M.A., 2005, The influence of tropospheric ozone, hydrothermal systems, and fires on atmospheric mercury emissions from natural sources: Reno, Nev., University of Nevada, Ph.D. thesis, 146 p.

Engle, M.A., Cozzarelli, I.M., and Smith, B.D., 2014, USGS investigations of water produced during hydrocarbon reservoir development: U.S. Geological Survey Fact Sheet 2014–3104, 4 p. (Also available at *http://pubs.er.usgs.gov/publication/fs20143104*.)

Engle, M.A., and Rowan, E.L., 2013, Interpretation of Na-Cl-Br systematics in sedimentary basin brines—Comparison of concentration, element ratio, and isometric log-ratio approaches: Mathematical Geosciences, v. 45, p. 87–101.

European Environmental Agency, 2008, Air pollution from electricity-generating large combustion plants: European Environmental Agency Technical Report No 4/2008, 43 p., accessed June 21, 2013, at *http://www.eea.europa.eu/publications/technical_report_2008_4*.

European Union Commission, 2009, Proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources: European Union Commission, accessed November 28, 2012, at *http://europa.eu/legislation_summaries/energy/renewable_energy/en0009_en.htm*.

Extension, 2014, Micanthus (Miscanthus x giganteus) for biofuel production: Extension, accessed November 29, 2014, at *http://www.extension.org/pages/26625/miscanthus-miscanthus-x-giganteus-for-biofuel-production#.VG5FhPnF-gZ*.

Faunt, C.C., ed., 2009, Groundwater availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766, 225 p. (Also available at *http://pubs.usgs.gov/pp/1766*.)

Feth, J.H.,and others, 1965, Preliminary map of the conterminous United States showing depth to and quality of shallowest ground water containing more than 1,000 parts per million of dissolved solids: U.S. Geological Survey Hydrologic Atlas 199, 31 p., 2 pl. (Also available at *http://pubs.er.usgs.gov/publication/ha199*.)

Finley, Bruce, 2012, Remedies not stopping water pollution at Commerce City refinery: Denver Post, May 2, 2012, accessed January 31, 2013, at *http://www.denverpost.com/environment/ci_20526481/remedies-not-stopping-water-pollution-at-commerce-city*.

Garrett, J.D., 2012, Concentrations, loads, and yields of selected constituents from major tributaries of the Mississippi and Missouri Rivers in Iowa, water years 2004–2008: U.S. Geological Survey Scientific Investigations Report 2012–5240, 61 p. (Also available at *http://pubs.usgs.gov/sir/2012/5240*.)

Gaswirth, S.B., Marra, K.R., Cook, T.A, Charpentier, R.R., Gautier, D.L., Higley, D.K., Klett, T.R., Lewan, M.D., Lillis, P.G., Schenk, C.J., Tennyson, M.E., and Whidden, K.J., 2013, Assessment of undiscovered oil resources in the Bakken and Three Forks Formations, Williston Basin Province, Montana, North Dakota, and South Dakota, 2013: U.S. Geological Survey Fact Sheet 2013–3013, 4 p. (Also available at *http://pubs.usgs.gov/fs/2013/3013/*.)

Gilliom, R.J., Barbash, J.E., Crawford, C.G., Hamilton, P.A., Martin, J.D., Nakagaki, Naomi, Nowell, L.H., Scott, J.C., Stackelberg, P.E., Thelin, G.P. and Wolock, D.M., 2006, Pesticides in the Nation’s streams and ground water, 1992–2001: U.S. Geological Survey Circular 1291, 173 p. (Also available at *http://pubs.usgs.gov/circ/2005/1291*.)

Gleick, P.H., 1994, Water and energy: Annual Review of Energy and the Environment, v. 19, no. 1, p. 267–299.

Gleick, P.H., and Cooley, H.S., 2009, Energy implications of bottled water: Environmental Research Letters, v. 4, no. 1, *http://dx.doi.org/10.1088/1748-9326/4/1/014009*.

Global CCS Institute, 2013, Carbon capture and sequestration projects: Global CCS Institute, accessed September 30, 2013, at *http://www.globalccsinstitute.com/projects/browse*.

Gray, S.J., Graumlich, L.J., Betancourt, J.L., and Pederson, G.T., 2004, A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D.: Geophysical Research Letters, v. 31, L12205.

Griffith, M.B., Norton, S.B., Alexander, L.C., Pollard, A.I., and LeDuc, S.D., 2012, The effects of mountaintop mines and valley fills on the physicochemical quality of stream ecosystems in the central Appalachians—A review: Science of the Total Environment, v. 417–418, p. 1–12.

Griffiths-Sattenspiel, Bevan, and Wilson, Wendy, 2009, The carbon footprint of water: Portland, Ore., River Network, 54 p., accessed July 5, 2012, at *http://www.rivernetwork.org/resource-library/carbon-footprint-water*.

Ground Water Protection Council, 2011, State oil and gas agency groundwater investigations and their role in advancing regulatory reforms: Ground Water Protection Council, 120 p. accessed November 20, 2014, at *http://www.gwpc.org/sites/default/files/State%20Oil%20%26%20Gas%20Agency%20Groundwater%20Investigations.pdf*.

Ground Water Protection Council and ALL Consulting, 2009, Modern shale gas development in the United States—A primer: U.S. Department of Energy–Office of Fossil Energy and National Energy Technology Laboratory, 98 p., accessed April 2, 2014, at *http://energy.gov/sites/prod/files/2013/03/f0/ShaleGasPrimer_Online_4-2009.pdf*.

Grubert, Emily, and Kitasei, Saya, 2010, How energy choices affect fresh water supplies—A comparison of U.S. coal and natural gas: Worldwatch Institute Briefing Paper 2, 20 p., accessed March 20, 2014, at *http://www.worldwatch.org/system/files/BP2.pdf*.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–B, 63 p. (Also available at *http://pubs.usgs.gov/pp/1400b/report.pdf*.)

Haines, S.S., Cook, Troy, Thamke, J.N., Davis, Andy, Healy, R.W., Hawkins, Sarah, and Engle, M.A., 2014, A framework for assessing water and proppant use and flowback water extraction associated with development of continuous petroleum resources: U.S. Geological Survey Fact Sheet 2014–3010, 6 p. (Also available at *http://pubs.usgs.gov/fs/2014/3010*.)

Haines, S.S.; Diffendorfer, J.E.; Balistrieri, Laurie; Berger, Byron; Cook, Troy; DeAngelis, Don; Doremus, Holly; Gautier, D.L.; Gallegos, Tanya; Gerritsen, Margot; Graffy, Elisabeth; Hawkins, Sarah; Johnson, K.M.; Macknick, Jordan; McMahon, Peter; Modde, Tim; Pierce, Brenda; Schuenemeyer, J.H.; Semmens, Darius; Simon, Benjamin; Taylor, Jason; and Walton-Day, Katie, 2013, A framework for quantitative assessment of impacts related to energy and mineral resource development: Natural Resources Research, v. 23, p. 3–17, *http://dx.doi.org/10.1007/s11053-013-9208-6*.

Hammack, R.W., Veloski, G.A., and Hodges, Greg, 2006, Helicopter surveys for locating wells and oilfield infrastructure, *in* 13th Annual International Petroleum Environmental Consortium Conference, San Antonio, Tex., October 17–20, 2006, Proceedings: Tulsa, Okla., University of Tulsa, 15 p., accessed March 20, 2014, at *http://ipec.utulsa.edu/Conf2006/Papers/Hammack_7.pdf*.

Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, Water budgets—Foundations for effective water-resources and environmental management: U.S. Geological Survey Circular 1308, 90 p. (Also available at *http://pubs.usgs.gov/circ/2007/1308*.)

Hetrick, L.H., 2011, Case study for well integrity over a full life cycle, *in* Proceedings of the technical workshops for the hydraulic fracturing study—Well construction and operation: U.S. Environmental Protection Agency EPA 600/R–11/046, p.122–129., accessed March 20, 2014, at *http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/upload/hydraulicfracturingstudywellconstructionandoperation.pdf*.

Heywood, C.E., and Yager, R.M., 2003, Simulated groundwater flow in the Hueco Bolson, an alluvial-basin aquifer system near El Paso, Texas: U.S. Geological Survey Water-Resources Investigations Report 2002–4108, 73 p. (Also available at *http://pubs.er.usgs.gov/publication/wri024108*.)

Hickey, J.J., and Vecchioli, John, 1986, Injection of liquid waste with emphasis on injection practices in Florida: U.S. Geological Survey Water Supply Paper 2281, 25 p. (Also available at *http://pubs.er.usgs.gov/publication/wsp2281*.)

Hightower, Mike, and Pierce, S.A., 2008, The energy challenge: Nature, v. 452, p. 285–286.

Hönisch, Bärbel; Hemming, N.G.; Archer, David; Siddall, Mark; and McManus, J.F., 2009, Atmospheric carbon dioxide concentration across the mid-Pleistocene transition: Science, v. 324, no. 5934, p. 1551–1554.

Ide, S.T., Friedmann, S.J., and Herzog, H.J., 2006, CO_2 leakage through existing wells—Current technology and regulations, *in* 8^{th} International Conference on Greenhouse Gas Control Technologies, Trondjheim, Norway, June 19–22, Proceedings: International Energy Agency Greenhouse Gas Research and Development Programme [IEAGHG], 6 p., accessed March 20, 2014, at *http://sequestration.mit.edu/pdf/GHGT8_Ide.pdf*.

Intergovernmental Panel on Climate Change, 2013, Climate change 2013—The physical science basis: Cambridge, United Kingdom, Cambridge University Press, accessed September 29, 2014, at *http://www.ipcc.ch/report/ar5/wg1/*.

International Energy Agency, 2012a, Key world energy statistics—2012: International Energy Agency, 79 p., accessed May 29, 2013, at *http://www.iea.org/publications/freepublications/publication/kwes.pdf/*.

International Energy Agency, 2012b, Golden rules for a golden age of gas—World Energy Outlook special report on unconventional gas: International energy Agency, 143 p., accessed March 20, 2014, at *http://www.worldenergyoutlook.org/goldenrules/*.

Jackson, R.E., Gorody, A.W., Mayer, B., Roy, J.W., Ryan, M.C., and van Sempvoory, D.R., 2013, Groundwater protection and unconventional gas extraction—The critical need for field-based hydrogeological research: Groundwater, v. 51, no. 4, p. 488–510.

Jevrejeva, S., Moore, J.C., Grinsted, A., and Woodworth, P.L., 2008: Recent global sea level acceleration started over 200 years ago?: Geophysical Research Letters, v. 35, L08715, *http://dx.doi.org/10.1029/2008GL033611*.

Johnson, R.C., Mercier, T.J., Brownfield, M.E., Pantea, M.P., and Self, J.G., 2009, Assessment of in-place oil shale resources of the Green River Formation, Piceance Basin, western Colorado: U.S. Geological Survey Fact Sheet 2009–3012, 6 p. (Also available at *http://pubs.usgs.gov/fs/2009/3012*.)

Johnson, R.C., Mercier, T.J., Brownfield, M.E., and Self, J.G., 2010, Assessment of in-place oil shale resources of the Green River Formation, Uinta Basin, Utah and Colorado: U.S. Geological Survey Fact Sheet 2010–3010, 4 p. (Also available at *http://pubs.usgs.gov/fs/2010/3010*.)

Jurgens, B.C., Burow, K.R., Dalgish, B.A., and Shelton, J.L., 2008, Hydrogeology, water chemistry, and factors affecting the transport of contaminants in the zone of contribution of a public-supply well in Modesto, eastern San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2008–5156, 78 p. (Also available at *http://pubs.usgs.gov/sir/2008/5156*).

Kappel, W.M., Williams, J.H., and Szabo, Zoltan, 2013, Water resources and shale gas/oil production in the Appalachian Basin—Critical issues and evolving developments: U.S. Geological Survey Open-File Report 2013–1137, 12 p. (Also available at *http://pubs.usgs.gov/of/2013/1137*.)

Kasprzyk-Hordern, Barbara, Dinsdale, R.M., and Guwy, A.J., 2009, The removal of pharmaceuticals, personal care products, endocrine disruptors and illicit drugs during wastewater treatment and its impact on the quality of receiving waters: Water Research, v. 43, p. 363–380.

Katz, B.G., Eberts, S.M., and Kauffman, L.J., 2011, Using Cl/Br ratios and other indicators to assess potential impacts on groundwater quality from septic systems—A review and examples from principal aquifers in the United States: Journal of Hydrology, v. 397, p. 151–166.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009, Estimated use of water in the United States in 2005: U.S. Geological Survey Circular 1344, 52 p., (Also available at *http://pubs.usgs.gov/circ/1344*.)

Keranen, K.M., Savage, H.M., Abers, G.A., and Cochran, E.S., 2013, Potentially induced earthquakes in Oklahoma, USA—Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence: Geology, v. 41, no. 6, p. 699–702.

Kharaka, Y.K., Ambats, Gil, Thordsen, J.J., and Davis, R.A., 1997, Deep well injection of brine from Paradox Valley, Colorado—Potential major precipitation problems remediated by nanofiltration: Water Resources Research, v. 33, p. 1013–1020.

Kharaka, Y.K., Thordsen, J.J., Hovorka, S.D., Nance, H.S., Cole, D.R., Phelps, T.J., and Knauss, K.G., 2009, Potential environmental issues of CO_2 storage in deep saline aquifers— Geochemical results from the Frio-I Brine Pilot test, Texas, USA: Applied Geochemistry, v. 24, p. 1106–112.

Kolker, Allan, Senor, C.L., and Quick, J.C., 2006, Mercury in coal and the impact of coal quality on mercury emissions from combustion systems: Applied Geochemistry, v. 21, p. 1821–1836.

Lerner, D.N., 2002, Identifying and quantifying urban recharge—A review: Hydrogeology Journal, v. 10, no. 1, p. 143–152.

Likens, Gene, 2011, Acid rain: The Encyclopedia of Earth, accessed March 15, 2014, at *http://www.eoearth.org/view/article/149814/*.

Lindberg, T.T., Bernhardt, E.S., Bier, Raven, Helton, A.M., Merola, R.B., Vengosh, Avner, and Di Giulio, R.T., 2011, Cumulative impacts of mountaintop mining on an Appalachian watershed: Proceedings of the National Academy of Sciences, v. 108, p. 20929–20934.

Llanos, Miguel, 2005, 44 oil spills found in southeast Louisiana: NBC News, September 19, 2005, accessed July 19, 2013, at *http://www.ncbnews.com/id/9365607/*.

Loeltz, O.J., and Leake, S.A., 1979, Relation between proposed developments of water resources and seepage from the All-American Canal, eastern Imperial Valley, California: U.S. Geological Survey Open-File Report 79–744, 83 p.

Lovelace, J.K., 2009, Methods for estimating water withdrawals for mining in the United States, 2005: U.S. Geological Survey Scientific Investigations Report 2009–5053, 7 p. (Also available at *http://pubs.usgs.gov/sir/2009/5053*.)

Lowry, M.E., Crist, M.A., and Tilstra, J.R., 1967, Geology and ground-water resources of Laramie County, Wyoming, *with a section on* Chemical quality of ground water and of surface water, by J.R. Tilstra: U.S. Geological Survey Water-Supply Paper 1834, 71 p. (Also available at *http://pubs.er.usgs.gov/publication/wsp1834*.)

Luckey, R.R., Gutentag, E.D., and Weeks, J.B., 1981, Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–652, 2 sheets, scale 1:2,500,000. (Also available at *http://pubs.er.usgs.gov/publication/ha652*.)

Luethi, Dieter; Le Floch, Martine; Bereiter, Bernard; Blunier, Thomas; Barnola, J.M.; Siegenthaler, Urs; Raynaud, Dominique; Jouzel, Jean; Fischer, Hubertus; Kawamura, Kenji; and Stocker, T.F., 2008, High-resolution carbon dioxide concentration record 650,000–800,000 years before present: Nature, v. 453, p. 379–382.

Lymn, Katherine, 2014, Projections—Southwest ND to grow to 82K by 2039—New oil technologies increase population, production guesses: The Dickonson Press, April 8, 2014, accessed September 25, 2014, at *http://www.thedickinsonpress.com/content/projections-southwest-nd-grow-82k-2039-new-oil-technologies-increase-population-production*.

Macknick, Jordan; Newmark, Robin; Heath, Garvin; and Hallett, K.C., 2011, A review of operational water consumption and withdrawal factors for electricity generating technologies: National Renewable Energy Laboratory Technical Report NREL/TP-6A20-50900, 21 p., accessed March 20, 2014, at *http://www.nrel.gov/docs/fy11osti/50900.pdf*.

Macknick, Jordan; Newmark, Robin; Heath, Garvin; and Hallett, K.C., 2012, Operational water consumption and withdrawal factors for electricity generating technologies—A review of existing literature: Environmental Research Letters, v. 7, *http://dx.doi.org/10.1088/1748-9326/7/4/045802*.

Macy, J.P., Brown, C.R., and Anderson, J.R., 2012, Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona 2010–2011: U.S. Geological Survey Open-File Report 2012–1102, 41 p. (Also available at *http://pubs.usgs.gov/of/2012/1102*.)

Mantell, M. E., 2010, Deep shale natural gas and water use, part two—Abundant, affordable, and still water efficient, *in* Water + energy in changing climates—Water/energy sustainability symposium at the 2010 GWPC Annual Forum, Pittsburgh, Pa., September 27–29, 2010, Proceedings: Ground Water Protection Council, 28 p., accessed March 20, 2014, at *http://www.gwpc.org/sites/default/files/event-sessions/20Mantell_Matthew.pdf*.

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p. (Also available at *http://pubs.usgs.gov/circ/1405*.)

McCarty, P.L., Bae, Jaeho, and Kim, Jeonghwan, 2011, Domestic wastewater treatment as a net energy producer—Can this be achieved?: Environmental Science and Technology, v. 45, p. 7100–7106.

McGuire, V.L., 2013, Water-level and storage changes in the High Plains aquifer, predevelopment to 2011 and 2009–11: U.S. Geological Survey Scientific Investigations Report 2012–5291, 15 p. (Also available at *http://pubs.usgs.gov/sir/2012/5291*.)

McMahon, P.B., Böhlke, J.K., Kauffman, L.J., Kipp, K.L., Landon, M.K., Crandall, C.A., Burow, K.R., and Brown, C.J., 2008, Source and transport controls on the movement of nitrate to public supply wells in selected principal aquifers of the United States: Water Resources Research, v. 44, W04401, *http://dx.doi.org/10.1029/2007WR006252*.

McMahon, P.B., Thomas, J.C., and Hunt, A.G., 2013, Groundwater ages and mixing in the Piceance Basin natural gas province: Environmental Science and Technology, v. 47, p. 13250–13257.

McNutt, M.K.; Chu, Steven; Lubchenco, Jane; Hunter, Tom; Dreyfus, Gabrielle; Murawski, S.A.; and Kennedy, D.M., 2012, Applications of science and engineering to quantify and control the Deepwater Horizon oil spill: Proceedings of the National Academy of Sciences, v. 109, no. 50, p. 20222–20228.

Meldrum, J., Nettles-Anderson, S., Heath, Garvin, and Macknick, Jordan, 2013, Life cycle water use for electricity generation—A review and harmonization of literature estimates: Environmental Research Letters, v. 8, *http://dx.doi.org/10.1088/1748-9326/8/1/015031*.

Meredith, Elizabeth; Wheaton, John; and Kuzara, Shawn, 2012, Coalbed-methane basics—Ten years of lessons from the Powder River Basin, Montana: Montana Bureau of Mines and Geology Information Pamphlet 6, 23 p.

Mishra, G.S., Glassley, W.E., and Yeh, Sonia, 2011, Realizing the geothermal electricity potential—Water use and consequences: Environmental Research Letters, v. 6, 034023, *http://dx.doi.org/10.1088/1748-9326/6/3/034023*.

Mohaghegh, Shahab, Bilgesu, H.I., Ertekin, Turgay, 1995, Production decline curves for low-pressure gas reservoirs undergoing simultaneous water production: SPE Formation Evaluation, v. 10, no. 1, p. 57–62.

Moorhouse, Jeremy; Huot, Marc; and Dyer, Simon, 2010, Drilling deeper—The in situ oil sands report card: Pembina Institute, 81 p., accessed March 20, 2014, at *http://www.pembina.org/pub/1981*.

Moran, M.J., Lapham, W.W., Rowe, B.L., and Zogorski, J.S., 2004, Volatile organic compounds in groundwater from rural private wells, 1986 to 1999: Journal of the American Water Resources Association, v. 40, no. 5, p. 1141–1157.

Mordick, Briana, 2011, Risks to drinking water from oil and gas wellbore construction and integrity—Case studies and lessons learned, *in* Proceedings of the technical workshops for the hydraulic fracturing study—Well construction and operation: U.S. Environmental Protection Agency, Office of Research and Development, EPA 600/R-11/046, p. 136–147, accessed March 20, 2014, at *http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/upload/hydraulicfracturingstudywellconstructionandoperation.pdf*.

Moreo, M.T., and Swancar, Amy, 2013, Evaporation from Lake Mead, Nevada and Arizona, March 2010 through February 2012: U.S. Geological Survey Scientific Investigations Report 2013–5229, 40 p. (Also available at *http://pubs.usgs.gov/sir/2013/5229/pdf/sir2013-5229.pdf*.)

Mudd, G.M., and Diesendorf, Mark, 2008, Sustainability of uranium mining and milling—Toward quantifying resources and eco-efficiency: Environmental Science and Technology, v. 42, no.7, p. 2624–2630.

Mueller, Steffen, 2010, Detailed report—2008 national dry mill corn ethanol survey: University of Illinois at Chicago, College of Engineering, 21 p., accessed July 16, 2013, at *http://ethanolrfa.3cdn.net/2e04acb7ed88d08d21_99m6idfc1.pdf*.

National Agriculture Statistics Service, 2014, National statistics for corn: U.S. Department of Agriculture, National Agriculture Statistics Service, accessed March 9, 2015, at *http://www.nass.usda.gov/Statistics_by_Subject/result.php?08638011-B478-3942-B44F-FA130ADDE283&sector=CROPS&group=FIELD%20CROPS&comm=CORN*.

National Atmospheric Deposition Program, 2014, Annual NTN maps by year: National Atmospheric Deposition Program, accessed September 25, 2014, at *http://nadp.sws.uiuc.edu/ntn/annualmapsByYear.aspx#2012*.

National Energy Technology Laboratory, 2006, Emerging issues for fossil energy and water: U.S. Department of Energy, National Energy Technology Laboratory report DOE/NETL-2006/1233, 49 p.

National Energy Technology Laboratory, 2010, Carbon dioxide enhanced oil recovery: U.S. Department of Energy, National Energy Technology Laboratory, 30 p., accessed March 20, 2014, at *http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/enhanced%20oil%20recovery/co2%20eor/NETL_CO2-EOR-Primer.pdf*.

National Energy Technology Laboratory, 2011, Estimating freshwater needs to meet future thermoelectric generation requirements—2011 update: U.S. Department of Energy, National Energy Technology Laboratory report DOE/NETL-2011/1523, accessed March 20, 2014, at *http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/DOE-NETL-2011-1523-WaterNeeds2011.pdf*.

National Energy Technology Laboratory, 2013, Modern shale gas development in the United States—An update: U.S. Department of Energy, National Energy Technology Laboratory, 79 p., accessed April 2, 2014, at *http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/shale-gas-primer-update-2013.pdf*.

National Hydropower Association, 2013, Pumped storage: National Hydropower Association, accessed July 11, 2013, at *http://www.hydro.org/tech-and-policy/technology/pumped-storage/*.

National Oceanic and Atmospheric Administration, 2013, Annual mean growth rate of CO2 at Mauna Loa: National Oceanic and Atmospheric Administration, accessed May 31, 2013, at *http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo_growth*.

National Petroleum Council, 2011, Plugging and abandonment of oil and gas wells [white paper no. 2-25], *in* Prudent development—Realizing potential of North America's abundant natural gas and oil resources [Working document of the NPC North American resource development study]: National Petroleum Council, 21 p., accessed March 20, 2014, at *http://www.npc.org/Prudent_Development-Topic_Papers/2-25_Well_Plugging_and_Abandonment_Paper.pdf*.

National Research Council, 2008a, Desalination—A national perspective: Washington, D.C., The National Academies Press, 255 p., accessed on July 5, 2012, at *http://www.nap.edu/catalog/12184.html*.

National Research Council, 2008b, Prospects for managed underground storage of recoverable water: Washington, D.C., The National Academies Press, 338 p., accessed June 25, 2013, at *http://www.nap.edu/catalog.php?record_id=12057*.

National Research Council, 2012, Induced seismicity potential in energy technologies: Washington, D.C., National Academies Press, 223 p., accessed March 20, 2014, at *http://www.nap.edu/catalog.php?record_id=13355*.

Newport, Frank, 2012, Americans still favor nuclear power a year after Fukushima: Gallup, March 26, 2012, accessed August 9, 2014, at *http://www.gallup.com/poll/153452/americans-favor-nuclear-power-year-fukushima.aspx*.

Nicot, J.-P.; Hebel, A.K.; Ritter, S.M.; Walden, Steven; Baier, Russ; Galusky, Peter; Beach, James; Kyle, Richard; Symank, Leigh; and Breton, Cari, 2011, Current and projected water use in the Texas mining and oil and gas industry: Austin, Tex., Texas Water Development Board, 357 p.

Nicot, J.-P., and Scanlon, B.R., 2012, Water use for shale-gas production in Texas, U.S.: Environmental Science and Technology, v. 46, no. 6, p. 3580–3586, *http://dx.doi.org/10.1021/es204602t*.

Nicot, J.-P., Scanlon, B.R., Reedy, R.C., and Costley, R.A., 2014, Source and fate of hydraulic fracturing water in the Barnett Shale—A historical perspective: Environmental Science and Technology, v. 48, p. 2464–2471.

Nordstrom, D.K., and Alpers, C.N., 1999, Negative pH, efflorescent mineralogy, and consequences for environmental restoration at the Iron Mountain superfund site, California: Proceedings of the National Academy of Sciences, v. 96, p. 3455–3462.

North Dakota Oil and Gas Division, 2014, North Dakota drilling and production statistics: North Dakota Oil and Gas Division, accessed April 9, 2014, at: *https://www.dmr.nd.gov/oilgas/stats/statisticsvw.asp*.

Northwest Power and Conservation Council, 2010, Grand Coulee dam—Impacts on fish: Northwest Power and Conservation Council, accessed on November 20, 2014, at *http://www.nwcouncil.org/history/GrandCouleeImpactsOnFish*.

Ohio Department of Natural Resources, 2014, Acid mine drainage abatement program: Ohio Department of Natural Resources, Division of Mineral Resources, accessed June 30, 2014, at *http://minerals.ohiodnr.gov/abandoned-mine-land-reclamation/acid-mine-drainage*.

Orange County Water District, 2014, Groundwater recharge operations: Orange County Water District, accessed September 25, 2014, at *http://www.ocwd.com/ProgramsProjects/GroundwaterRecharge.aspx*.

Osborn, S.G., Vengosh, Avner, Warner, N.R., and Jackson, R.B., 2011, Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing: Proceedings of the National Academy of Sciences, v. 108, p. 8172–8176.

Pagani, Mark; Liu, Zhonghui; LaRiviere, Jonathan; and Ravelo, A.C., 2010, High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations: Nature Geoscience, v. 3 p. 27–30.

Pandey, V.C., and Singh, Nandita, 2010, Impact of fly ash incorporation in soil systems: Agriculture, Ecosystems, and Environment, v. 136, p. 16–27.

Pashin, J.C., 2007, Hydrodynamics of coalbed methane reservoirs in the Black Warrior Basin—Key to understanding reservoir performance and environmental issues: Applied Geochemistry, v. 22, no. 10, p. 2257–2272.

Passarello, M.C., Sharp, J.M., Jr., and Pierce, S.A., 2012, Estimating urban-induced artificial recharge—A case study for Austin, Texas: Environmental and Engineering Geoscience, v. 18, no. 1, p. 25–36.

Pate, Ron; Hightower, Mike; Cameron, Chris; and Einfeld, Wayne, 2007, Overview of energy-water interdependencies and the emerging energy demands on water resources: Sandia National Lab Report SAND 2007-1349C, 20 p.

Pennsylvania Department of Environmental Protection, 2012, 2012—Permits issued and wells drilled maps: Pennsylvania Department of Environmental protection, Office of Oil and Gas Management, accessed April 30, 2013, at *http://files.dep.state.pa.us/OilGas/BOGM/BOGMPortalFiles/OilGasReports/2012/2012Wellspermitted-drilled.pdf*.

Petit, J.R, Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotiyakov, V. M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., and Stievenard, M., 1999, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica: Nature, v. 399, p. 429–436.

Pollastro, R.M., Cook, T.A., Roberts, L.N.R., Schenk, C.J., Lewan, M.D., Anna, L.O., Gaswirth, S.B., Lillis, P.G., Klett, T.R., and Charpentier, R.R., 2008, Assessment of undiscovered oil resources in the Devonian-Mississippian Bakken Formation, Williston Basin Province, Montana and North Dakota, 2008: U.S. Geological Survey Fact Sheet 2008–3021, 2 p. (Also available at *http://pubs.usgs.gov/fs/2008/3021*.)

Power Reactor Information System, 2014, Country statistics—United States of America: International Atomic Energy Agency, Power Reactor Information System, accessed March 27, 2014, at *http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=US*.

Price, P.H., Hare, C.E., McCue, J.B., and Hoskins, H.A., 1937, Salt brines of West Virginia: West Virginia Geological Survey Report VIII, 203 p.

Pyne, R.D.G., 2005, Aquifer storage recovery—A guide to groundwater recharge through wells, (2d ed.): Gainesville, Fla., ASR Press, 620 p.

Qi, S.L., 2010, Digital map of aquifer boundary for the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Data Series 543. (Also available at *http://pubs.usgs.gov/ds/543/*.)

Ray, R.D., and Douglas, B.C., 2011, Experiments in reconstructing twentieth-century sea levels: Progress in Oceanography, v. 91, p. 496–515.

Reisner, Marc, 1993, Cadillac desert—The American West and its disappearing water (revised edition): New York, Penguin Books, 582 p.

Renewable Fuels Association, 2013, Biorefinery locations: Renewable Fuels Association, accessed November 8, 2013, at *http://www.ethanolrfa.org/bio-refinery-locations/*.

Rostad, C.E., 2007, Studies on disinfection by-products and drinking water: U.S. Geological Survey Fact Sheet 2004–3032, 4 p.

Royal Society of Canada Expert Panel, 2010, Environmental and health impacts of Canada's oil sands industry: Ottawa, Ontario, Royal Society of Canada, 440 p., accessed March 20, 2014, at *http://rsc-src.ca/en/expert-panels/rsc-reports/environmental-and-health-impacts-canadas-oil-sands-industry*.

Ruhl, Laura; Vengosh, Avner; Dwyer, G.S.; Hsu-Kim, Heileen; and Deonarine, Amrika, 2010, Environmental impacts of the coal ash spill in Kingston, Tennessee—An 18-month survey: Environmental Science and Technology, v. 44, p. 9272–9278.

Ruhl, Laura; Vengosh, Avner; Dwyer, G.S.; Hsu-Kim, Heileen; Schwartz, Grace; Romanski, Autumn; and Smith, S.D., 2012, The impact of coal combustion residue effluent on water resources—A North Carolina example: Environmental Science and Technology, v. 46, p. 12226–12233.

Runkel, R.L., Kimball, B.A., Walton-Day, Katherine, Verplank, P.L., and Broshears, R.E., 2012, Evaluating remedial alternatives for an acid mine drainage stream—A model post audit: Environmental Science and Technology, v. 46, no. 1, p. 340–347.

Rutsch, M., Rieckermann, J., Cullmann, J., Ellis, J.B., Vollertsen, J., and Krebs, P., 2008, Towards a better understanding of sewer exfiltration: Water Research, v. 49, p. 2385–2394.

San Diego County Water Authority, 2013, Canal lining projects: San Diego County Water Authority Fact Sheet, 2 p., accessed July 11, 2014, at *http://sdcwa.org/sites/default/files/canallining_fs.pdf*.

Sanders, K.T., and Webber, M.E., 2012, Evaluating the energy consumed for water use in the United States: Environmental Research Letters, v. 7, 11 p., *http://dx.doi.org/10.1088/1748-9326/7/3/034034*.

Scanlon, B.R., Duncan, Ian, and Reddy, R.C., 2013, Drought and the water-energy nexus in Texas: Environmental Research Letters, v. 8, 14 p., *http://dx.doi.org/10.1088/1748-9326/8/4/045033*.

Scanlon, B.R., Reddy, R.C., and Nicot, J.-P., 2014, Comparison of water use for hydraulic fracturing for unconventional oil and gas versus conventional oil: Environmental Science and Technology, v. 48, no. 20, p. 12386–12393.

Schenk, C.J., and Pollastro, R.M., 2002, Natural gas production in the United States: U.S. Geological Survey Fact Sheet 113–01, 2 p. (Also available at *http://pubs.usgs.gov/fs/fs-113-01/*.)

Schirmer, Mario; Leschik, Sebastian; and Musolff, Andreas, 2013, Current research in urban hydrogeology—A review: Advances in Water Resources, v. 51, p. 280–291.

Schmidt, C.W., 2013, Estimating wastewater impacts from fracking: Environmental Health Perspectives, v. 121, p. a117.

Schweinfurth, S.P., 2003, Coal—A complex natural resource: U. S. Geological Survey Circular 1143, p. 37. (Also available at *http://pubs.er.usgs.gov/publication/cir1143*.)

Scott, D.C., and Luppens, J.A., 2013, Assessment of coal geology, resources, and reserve base in the Powder River Basin, Wyoming and Montana: U.S. Geological Survey Fact Sheet 2012–3143, 6 p. (Also available at *http://pubs.usgs.gov/fs/2012/3143*.)

Shapouri, Hosein, and Gallagher, Paul, 2005, USDA's 2002 ethanol cost-of-production survey: U.S. Department of Agriculture, Agricultural Economic Report Number 841, 19 p.

Shedlock, R.J., 1980, Saline water at the base of the glacial-outwash aquifer near Vincennes, Knox County, Indiana: U.S. Geological Survey Water-Resources Investigations 80–65, 54 p.

Shorney-Darby, Holly; Titus, Hala; Cardenas, Myriam; and Borboa, Gil, 2011, Restoring Santa Monica’s MTBE-contaminated groundwater supply: Journal—American Water Works Association, v. 103, no. 11, p. 38–44.

Soeder, D.J., and Kappel, W.M., 2009, Water resources and natural gas production from the Marcellus Shale: U.S. Geological Survey Fact Sheet 2009–3032, 6 p. (Also available at *http://pubs.usgs.gov/fs/2009/3032*.)

Solley, W.B., Pierce, R.R., and Perlman, H.A., 1998, Estimated use of water in the United States in 1995: U.S. Geological Survey Circular 1200, 86 p. (Also available at *http://pubs.er.usgs.gov/publication/cir1200*.)

Stein, David, Griffin, T.J., Jr., and Dusterhoft, Dale, 2003, Cement pulsation reduces remedial cementing costs: GasTIPS, v. 9, no. 1, p. 22–24, accessed March 20, 2014, at *http://www.ernstversusencana.ca/wp-content/uploads/2013/04/CementPulsationReducesRemedialCementing-2003.pdf*.

Subcommittee on Ground Water, 2013, A national framework for ground-water monitoring in the United States: The Advisory Committee on Water Information, 168 p., accessed on November 25, 2013, at *http://acwi.gov/sogw/ngwmn_framework_report_july2013.pdf*.

Teodoriu, Catalin; and Falcone, Gioia, 2008, Comparing completion design in hydrocarbon and geothermal wells—The need to evaluate the integrity of casing connections subject to thermal stresses: Geothermics, v. 38, no. 2, p. 238–246.

Thomas, J.C., and McMahon, P.B., 2012, Overview of groundwater quality in the Piceance Basin, western Colorado, 1946–2009: U.S. Geological Survey Scientific Investigations Report 2012–5198, 204 p. (Also available at *http://pubs.usgs.gov/sir/2012/5198*.)

Thomas, J.C., Moore, J.L., Schaffrath, K.R., Dupree, J.A., Williams, C.A., and Leib, K.J., 2013, Characterization and data-gap analysis of surface-water quality data in the Piceance study area, western Colorado, 1959–2009: U.S. Geological Survey Scientific Investigations Report 2013–5015, 74 p. (Also available at *http://pubs.usgs.gov/sir/2013/5015*.)

Tidwell, V.C., Malczynski, L.A., Kohos, P.H., Klise, G.T., and Shuster, Erik, 2013, Potential impacts of electric power production utilizing natural gas, renewables and carbon capture and sequestration on U.S. freshwater resources: Environmental Science and Technology, v. 47, p. 8940–8947.

Toccalino, P.L., and Hopple, J.A., 2010, The quality of our Nation’s waters—Quality of water from public-supply wells in the United States, 1993–2000—Overview of major findings: U.S. Geological Survey Circular 1346, 58 p. (Also available at *http://pubs.usgs.gov/circ/1346*.)

U.S. Bureau of Land Management, 2012, Oil shale/tar sands guide: U.S. Bureau of Land Management, accessed November 24, 2014, at *http://ostseis.anl.gov/guide/index.cfm*.

U.S. Census Bureau, 2014, American fact finder: U.S. Census Bureau, accessed November 21, 2014, at *http://factfinder2.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=AHS_2011_C04AO&prodType=table*.

U.S. Department of Agriculture, 2010, Farm and ranch irrigation survey (2008): U.S. Department of Agriculture, National Agricultural Statistics Service, AC-07-22-1, 259 p., accessed November 28, 2013, at *http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/index.php*.

U.S. Department of Energy, 2006, Energy demands on water resources—Report to Congress on the interdependency of energy and water, 80 p., accessed March 20, 2014, at *http://www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf*.

U.S. Department of Energy, 2009, Concentrating solar power commercial application study—Reducing water consumption of concentrating solar power electricity generation. Report to Congress: U.S. Department of Energy, 24 p., accessed March 20, 2014, at *http://www1.eere.energy.gov/solar/pdfs/csp_water_study.pdf*.

U.S. Department of Energy, 2010, San Diego solar panels generate clean electricity along with clean water: U.S. Department of Energy, accessed June 20, 2013, at *http://energy.gov/articles/san-diego-solar-panels-generate-clean-electricity-along-clean-water*.

U.S. Department of Energy, 2012, Ethanol: U.S. Department of Energy, accessed December 13, 2012, at *http://www.fueleconomy.gov/feg/ethanol.shtml*.

U.S. Department of Energy, 2013a, Nevada deploys first U.S. commercial, grid-connected enhanced geothermal system: U.S. Department of Energy, accessed November 21, 2014, at *http://energy.gov/articles/nevada-deploys-first-us-commercial-grid-connected-enhanced-geothermal-system*.

U.S. Department of Energy, 2013b, U.S. energy sector vulnerabilities to climate change and extreme weather: U.S. Department of Energy, DOE/PI-0013, 83 p., accessed December 17, 2013, at *http://energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather*.

U.S. Department of Energy, 2013c, New infographic and projects to keep your energy bills out of hot water: U.S. Department of Energy, accessed October 14, 2013, at *http://energy.gov/articles/new-infographic-and-projects-keep-your-energy-bills-out-hot-water*.

U.S. Department of Energy, 2014, The water-energy nexus—Challenges and opportunities: U.S. Department of Energy, 238 p., accessed November 24, 2014, at *http://energy.gov/downloads/water-energy-nexus-challenges-and-opportunities*.

U.S. Energy Information Administration, 2010, Energy used as a nonfuel (feedstock)—2010 Manufacturing Energy Consumption Survey data: U.S. Energy Information Administration, accessed February 6, 2014, at *http://www.eia.gov/consumption/manufacturing/data/2010/#r2*.

U.S. Energy Information Administration, 2011, Lower 48 states shale plays: U.S. Energy Information Administration, accessed on September 29, 2014, at *http://www.eia.gov/oil_gas/rpd/shale_gas.pdf*.

U.S. Energy Information Administration, 2012a, Annual Energy Review—2011: U.S. Energy Information Administration, accessed November 28, 2012, at *http://www.eia.gov/aer*.

U.S. Energy Information Administration, 2012b, Annual energy outlook 2012 with projections to 2035: U.S. Energy Information Administration, DOE/EIA-0383(2012), 240 p., accessed March 20, 2014, at *http://www.eia.gov/forecasts/aeo/pdf/0383(2012).pdf*.

U.S. Energy Information Administration, 2012c, Most states have renewable portfolios: Today in Energy [U.S. Energy Information Administration], February 3, 2012, accessed November 13, 2013, at *http://www.eia.gov/todayinenergy/detail.cfm?id=4850*.

U.S. Energy Information Administration, 2013a, Brazil—Overview: U.S Energy Information Administration, accessed November 24, 2014, at *http://www.eia.gov/countries/analysisbriefs/brazil/brazil.pdf*.

U.S. Energy Information Administration, 2013b, Natural-gas fired turbines are generally used to meet peak electricity load: Today in Energy [U.S. Energy Information Administration], October 1, 2013, accessed February 12, 2014, at *http://www.eia.gov/todayinenergy/detail.cfm?id=13191*.

U.S. Energy Information Administration, 2013c, U.S. natural gas, wet after lease separation proved reserves: U.S. Energy Information Administration, accessed February 14, 2013, at *http://tonto.eia.gov/dnav/ng/hist/rngr21nus_1a.htm*.

U.S. Energy Information Administration, 2014a, Electric power monthly—October 2014: U.S. Energy Information Administration, accessed November 20, 2014, at *http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_01_a*.

U.S. Energy Information Administration, 2014b, Monthly energy review—September 2014: U.S. Energy Information Administration, DOE/EIA-0035(2014/09), 201 p., accessed September 30, 2014, at *http://www.eia.gov/totalenergy/data/monthly*.

U.S. Energy Information Administration, 2014c, 2013 domestic uranium production report: U.S. Energy Information Administration, 14 p., accessed October 31, 2014, at *http://www.eia.gov/uranium/production/annual/archive/dupr2012.pdf*.

U.S. Environmental Protection Agency, 1999, Achieving clean air and clean water—The report of the Blue Ribbon Panel on oxygenates in gasoline: U.S. Environmental Protection Agency, EPA 420-R-99-021, 116 p., accessed July 11, 2014, at *http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P10003YU.txt*.

U.S. Environmental Protection Agency, 2002, Community water system survey 2000, v. 1—Overview: U.S. Environmental Protection Agency, EPA/815/R-02/005A, 58 p., accessed July 20, 2012, at *http://water.epa.gov/infrastructure/drinkingwater/pws/cwssvr.cfm*.

U.S. Environmental Protection Agency, 2003, Design Manual—Removal of arsenic from drinking water by adsorptive media: U.S. Environmental Protection Agency, EPA/600/R-03/D19, 85 p., accessed October 14, 2013, at *http://nepis.epa.gov/EPA/html/DLwait.htm?url=/Exe/ZyPDF.cgi?Dockey=30002K50.PDF*.

U.S. Environmental Protection Agency, 2004, State actions banning MTBE (statewide): U.S. Environmental Protection Agency, EPA-420-B-04-009, accessed October 24, 2012, at *http://www.epa.gov/mtbe/420b04009.pdf*.

U.S. Environmental Protection Agency, 2011a, Opportunities for combined heat and power at wastewater treatment facilities—Market analysis and lessons from the field: U.S. Environmental Protection Agency, EPA-430-R-11-018, 50 p., accessed October 17, 2013, at *http://www.epa.gov/chp/documents/wwtf_opportunities.pdf*.

U.S. Environmental Protection Agency, 2011b, Plan to study the potential impacts of hydraulic fracturing on drinking water resources: U.S. Environmental Protection Agency, Office of Research and Development, EPA/600/R-11/122, 190 p., accessed March 20, 2014, at *http://region8water.colostate.edu/PDFs/hf_study_plan_110211_final_508.pdf*.

U.S. Environmental Protection Agency, 2012a, EPA and NHTSA set standards to reduce greenhouse gases and improve fuel economy for model years 2017–2025 cars and light trucks: U.S. Environmental Protection Agency, EPA-420-F-12-051, 10 p., accessed February 3, 2014, at *http://www.epa.gov/otaq/climate/documents/420f12051.pdf*.

U.S. Environmental Protection Agency, 2012b, FY2011 annual report on the underground storage tank program: U.S. Environmental Protection Agency, EPA 510-R-12-001, 6 p., accessed March 12, 2014, at *http://www.epa.gov/oust/pubs/annrpts.html*.

U.S. Environmental Protection Agency, 2012c, Classes of wells: U.S. Environmental Protection Agency, accessed April 5, 2013, at *http://water.epa.gov/type/groundwater/uic/wells.cfm*.

U.S. Environmental Protection Agency, 2013a, Coal combustion residuals—Proposed rules: U.S. Environmental Protection Agency, accessed December 23, 2013, at *http://www.epa.gov/solidwaste/nonhaz/industrial/special/fossil/ccr-rule/index.htm*.

U.S. Environmental Protection Agency, 2013b, Federal action to address impacts of uranium contamination in the Navajo Nation—Five-year plan summary report: U.S. Environmental Protection Agency, 66 p., accessed May 13, 2013, at *http://www/epa.gov/region9/superfund/navajo-nation/pdf/NavajoUranniumReport2013.pdf*.

U.S. Environmental Protection Agency, 2013c, Inventory of U.S. greenhouse gas emissions and sinks—1900–2011: U.S. Environmental Protection Agency, EPA 430-R-13-001, 503 p., accessed March 20, 2014, at *http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2013-Main-Text.pdf*.

U.S. Environmental Protection Agency, 2013d, Water quality assessment and total maximum daily loads information: U.S. Environmental Protection Agency, accessed December 31, 2013, at *http://www.epa.gov/water/ir/*.

U.S. Environmental Protection Agency, 2014a, Contaminants of emerging concern: U.S. Environmental Protection Agency, accessed November 21, 2014, at *http://water.epa.gov/scitech/cec/*.

U.S. Environmental Protection Agency, 2014b, Cooling water intakes [regarding section 316(b) of the Clean Water Act]: U.S. Environmental Protection Agency, accessed August 9, 2014, at *http://water.epa.gov/lawsregs/lawsguidance/cwa/316b/*.

U.S. Environmental Protection Agency, 2014c, Economics of biofuels: U.S. Environmental Protection Agency, accessed November 20, 2014, at *http://yosemite.epa.gov/ee/epa/eed.nsf/pages/Biofuels.html*.

U.S. Environmental Protection Agency, 2014d, Mid-Atlantic mountaintop mining: U.S. Environmental Protection Agency, accessed November 20, 2014, at *http://www.epa.gov/region3/mtntop/*.

U.S. Environmental Protection Agency, variously dated, External combustion sources, chap. 1 *of* Stationary point and area sources. AP 42—Compilation of air pollutant emission factors, v. 1 (5th ed.): U.S. Environmental Protection Agency, accessed November 5, 2014, at *http://www.epa.gov/ttn/chief/ap42/ch01/index.html*.

U.S. Fish and Wildlife Service, 2014, Endangered species: U.S. Fish and Wildlife Service, accessed November 21, 2014, at *http://www.fws.gov/endangered/*.

U.S. Forest Service, 2014, Stream temperature modeling and monitoring: U.S. Forest Service, Rocky Mountain Research Station–Air, Water, and Aquatic Environments Program, accessed January 8, 2014, at *http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temperature.shtml*.

U.S. General Accounting Office, 2003, Freshwater supply—States' views of how Federal agencies could help them meet the challenges of expected shortages: U.S. General Accounting Office GAO-03-514, 110 p., accessed March 20, 2014, at *http://www.gao.gov/new.items/d03514.pdf*.

U.S. Geological Survey, 2003, Assessment of undiscovered oil and gas resources of the Uinta-Piceance Province of Colorado and Utah: U.S. Geological Survey Fact Sheet 157–02, 2 p. (Also available at *http://pubs.usgs.gov/fs/157-02*.)

U.S. Geological Survey, 2013, National assessment of geologic carbon dioxide storage resources—Summary: U.S. Geological Survey Fact Sheet 2013–3020, 6 p. (Also available at *http://pubs.usgs.gov/fs/2013/3020*.)

U.S. Geological Survey, 2014a, Acid rain: U.S. Geological Survey, accessed November 21, 2014, at *http://water.usgs.gov/edu/acidrain.html*.

U.S. Geological Survey, 2014b, High Plains Aquifer groundwater network: U.S. Geological Survey, Office of Groundwater, Groundwater Water Watch, accessed January 7, 2014, at *http://groundwaterwatch.usgs.gov/Net/OGWNetwork.asp?ncd=hpn*.

U.S. Geological Survey, 2015, Map of below normal 7-day average streamflow compared to historical streamflow for the day of year: U.S. Geological Survey WaterWatch, accessed March 9, 2015, at *http://waterwatch.usgs.gov/?state=us&map_type=dryw&web_type=map*.

U.S. Government Accountability Office, 2010, Energy-water nexus—A better and coordinated understanding of water resources could help mitigate the impacts of potential oil shale development: U.S. Government Accountability Office, GAO-11-35, 69 p., accessed March 20, 2014, at *http://www.gao.gov/new.items/d1135.pdf*.

U.S. Government Accountability Office, 2011a, Energy-water nexus—Amount of energy needed to supply, use, and treat water is location-specific and can be reduced by certain technologies and approaches: U.S. Government Accountability Office, GAO-11-225, 35 p., accessed June 24, 2013, at *http://www.gao.gov/products/GAO-11-225*.

U.S. Government Accountability Office, 2011b, Energy development and water use—Impacts of potential oil shale development on water resources: U.S. Government Accountability Office, GAO-11-929T, 14 p., accessed March 20, 2014, at *http://www.gao.gov/new.items/d11929t.pdf*.

U.S. Nuclear Regulatory Commission, 1997, Final environmental impact statement to construct and operate the Crownpoint Uranium Solution Mining Project, Crownpoint, New Mexico: U.S. Nuclear Regulatory Commission, NUREG–1508, accessed March 20, 2014, at *http://pbadupws.nrc.gov/docs/ML0821/ML082170248.pdf*.

U.S. Pipeline and Hazardous Materials Safety Administration, [2014a], Pipeline basics: U.S. Department of Transportation, U.S. Pipeline and Hazardous Materials Safety Administration, accessed March 12, 2014, at *http://primis.phmsa.dot.gov/comm/PipelineBasics.htm?nocache=22*.

U.S. Pipeline and Hazardous Materials Safety Administration, [2014b], Significant pipeline incidents: U.S. Department of Transportation, U.S. Pipeline and Hazardous Materials Safety Administration, accessed March 12, 2014, at *http://primis.phmsa.dot.gov/comm/reports/safety/SigPSI.html?nocache=9281*.

U.S. Water News Online, 1996, Santa Monica water supply threatened by MTBE: U.S. Water News Online, accessed October 24, 2012, at *http://www.uswaternews.com/archives/arcquality/6smonica.html*.

University of Nebraska–Lincoln, Conservation and Survey Division, 2012, Groundwater-level changes in Nebraska—Predevelopment to spring 2011: Lincoln, Nebr., University of Nebraska–Lincoln, Conservation and Survey Division, digital map graphic, accessed September 29, 2014, at *http://snr.unl.edu/data/water/groundwatermaps.asp*.

Veil, J.A., 2007, Use of reclaimed water for power plant cooling: U.S. Department of Energy, Argonne National Laboratory, Environmental Science Division, ANL/EVS/R-07/3, 60 p.

Veil, J.A., Puder, M.G., Elcock, Deborah, and Redweik, R.J., Jr., 2004, A white paper describing produced water from production of crude oil, natural gas, and coal bed methane: U.S. Department of Energy, Argonne National Laboratory, 87 p., accessed March 20, 2014, at *http://www.circleofblue.org/waternews/wp-content/uploads/2010/08/prodwaterpaper1.pdf*.

Verstraeten, I.M., Carr, J.D., Steele, G.V., Thurman, E.M., Bastian, K.C., and Dormedy, D.F., 1999, Surface water-groundwater interaction—Herbicide transport into municipal collector wells: Journal of Environmental Quality, v. 28, p. 1396–1405.

Walton-Day, Katherine, Runkel, R.L., and Kimball, B.A., 2012, using spatially detailed water-quality data and solute-transport modeling to support total maximum daily load development: Journal of the American Water Resources Association, v. 48, no. 5, p. 949–969.

Water Environment Research Foundation, 2011, Energy production and efficiency research—The roadmap to net-zero energy: Water Environment Research Foundation fact sheet ENER1fs, 8 p., accessed on July 11, 2014, at *http://www.werf.org/c/2011Challenges/Energy_Optimization_.aspx*.

West Virginia Department of Environmental Protection, 2010, Oil and gas production data—Abandoned wells list: West Virginia Department of Environmental Protection, Office of Oil and Gas, accessed November 6, 2013, at *http://www/dep.wv.gov/oil-and-gas/databaseinfo/Pages/default.aspx*.

Williams, C.F., Reed, M.J., Mariner, R.H., DeAngelo, Jacob, and Galanis, S.P., Jr., 2008, Assessment of moderate- and high-temperature geothermal resources of the United States: U.S. Geological Survey Fact Sheet 2008–3082, 4 p. (Also available at *http://pubs.usgs.gov/fs/2008/3082*.)

Wiltsee, G., 2000, Lessons learned from existing biomass power plants: National Renewable Energy Laboratory, NREL/SR-570-26946, 143 p., accessed November 20, 2014, at *http://www.nrel.gov/docs/fy00osti/26946.pdf*.

Winograd, I.J., Szabo, B.J., Coplen, T.B., and Riggs, A.C., 1988, A 250,000-year climatic record from Great Basin vein calcite—Implications for the Milankovitch theory: Science, v. 242, p.1275–1280.

Wittenberg, H., and Aksoy, H., 2010, Groundwater intrusion into leaky sewer systems: Water Science and Technology, v. 62, p. 92–98.

World Coal Association, 2014, Coal to liquids: World Coal Association, accessed November 20, 2014, at *http://www.worldcoal.org/coal/uses-of-coal/coal-to-liquids/*.

World Nuclear Association, 2014, Nuclear power in the USA: World Nuclear Association, accessed August 9, 2014, at *http://www.world-nuclear.org/info/inf41.html*.

Wright, C.K., and Wimberly, M.C., 2013, Recent land use change in the western corn belt threatens grasslands and wetlands: Proceedings of the National Academy of Sciences of the United States of America, v. 110, no. 10, p. 4134–4139.

Wu, May, and Chiu, Yiwen, 2011, Consumptive water use in the production of ethanol and petroleum gasoline—2011 update: U.S. Department of Energy, Argonne National Laboratory, ANL/ESD/09-1–Update, 84 p.

Wu, May, Mintz, M., Wang, M., and Arora, S., 2009, Consumptive water use in the production of ethanol and petroleum gasoline: U.S. Department of Energy, Argonne National Laboratory, ANL/ESD/09-1, 78 p., accessed March 20, 2014, at *http://www.circleofblue.org/waternews/wp-content/uploads/2010/09/Water-Consumption-in-Ehtanol-and-Petroleum-Production.pdf*.

Wyoming Oil and Gas Conservation Commission, 2011, Drilling permits, Powder River Basin: Wyoming Oil and Gas Conservation Commission, accessed January 29, 2011, at *http://wogcc.state.wy.us*.

Wyoming Oil and Gas Conservation Commission, 2014, Water production, Powder River Basin: Wyoming Oil and Gas Conservation Commission, accessed October 31, 2014, at *http://wogcc.state.wy.us*.

Zogorski, J.S., Carter, J.M., Ivahnenko, Tamara, Lapham, W.W., Moran, M.J., Rowe, B.L., Squillace, P.J., and Toccalino, P.L., 2006, The quality of our Nation's waters—Volatile organic compounds in the Nation's ground water and drinking water supply wells: U.S. Geological Survey Circular 1292, 101 p. (Also available at *http://pubs.usgs.gov/circ/circ1292*.)

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